

# Nuclear Data Research at the Gaerttner LINAC Center at RPI

*Yaron Danon*

*Director Gaerttner LINAC Center, Nuclear Engineering Program Director  
Rensselaer Polytechnic Institute, Troy, NY, 12180*



**Transformative Hadron Beamlines Workshop**

July 21-23, 2014, Brookhaven National Laboratory



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# Collaboration (Nuclear Data)

- **RPI**

- Faculty:
  - Dr. Y. Danon, Dr. E. Liu
- Staff
  - P. Brand - Technical Manager
  - M. Gray, M. Strock, A. Kerdoun - Linear Accelerator Technicians
- **Graduate Students (nuclear data related only):**
  - Z. Blain – Fission neutrons
  - A. Daskalakis – Fast Neutron scattering
  - N. Thompson – LSDS capture
  - B. McDermott – KeV Capture detector,
  - A. Weltz – Assay of used nuclear fuel/Solid-State Neutron Detector
  - K. Ramic – Thermal neutron scattering
  - C. Wendorff – Thermal neutron scattering
  - A. Youmans – KeV neutron scattering



**Group Openings**

- Postdoc
- 2 graduate students

- **KAPL**

- Dr. T. Donovan, Dr. G. Leinweber, Dr. D. Barry, Dr. M. Rapp, B. Epping, and Dr. R. Block



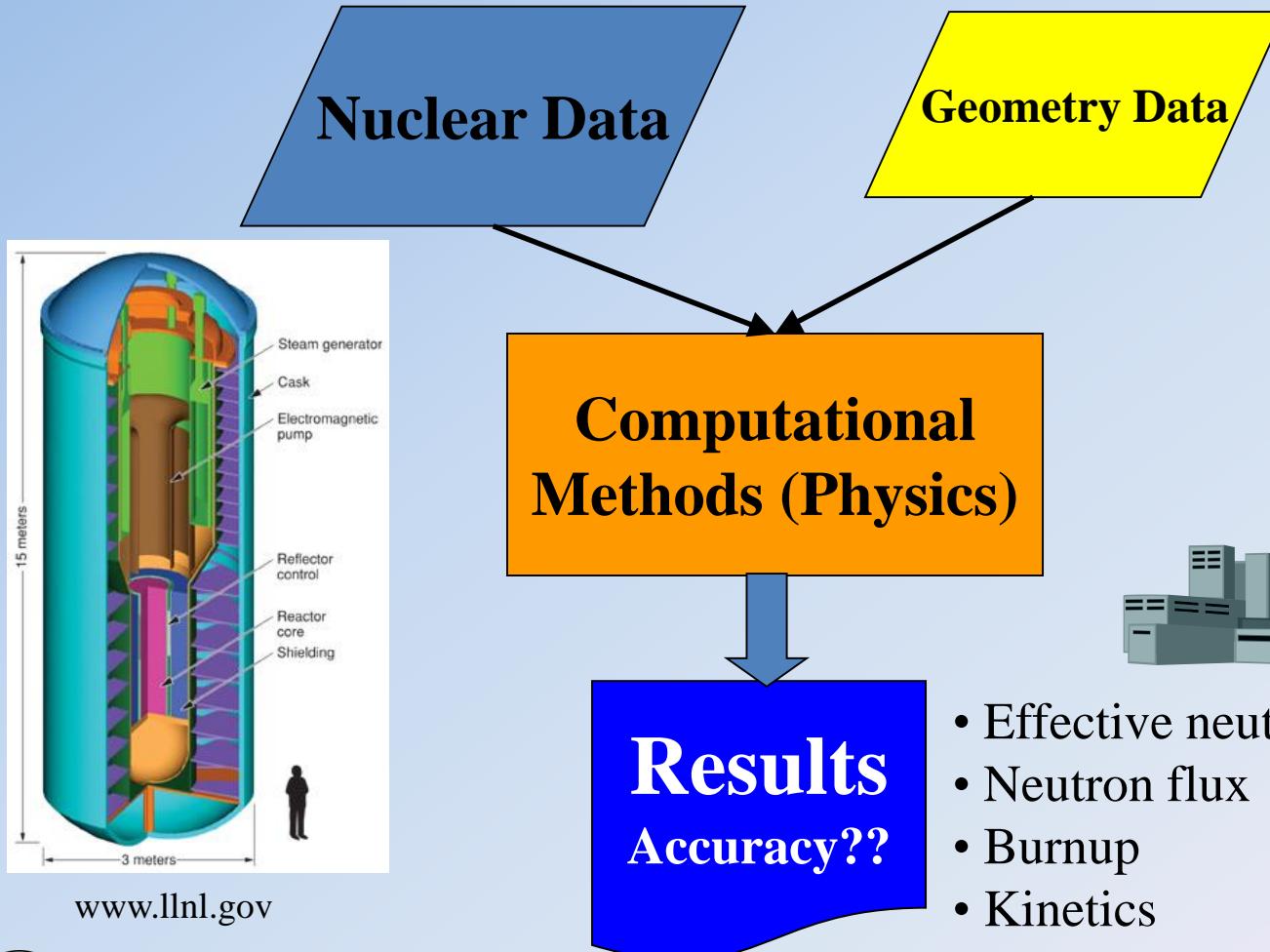
# Outline

- Why Nuclear Data is important
- Simple Physics of Nuclear Reactions
- The RPI Gaerttner LINAC laboratory
- Overview of Experimental Results
  - Resonance Region Transmission and Capture Measurements
  - Capture to Fission Ratio
  - High Energy Transmission
  - Filtered Beam Measurements
  - High Energy Scattering
  - Resonance Scattering
  - Fission Neutrons
  - The Lead Slowing Down Spectrometer
- New capabilities in development

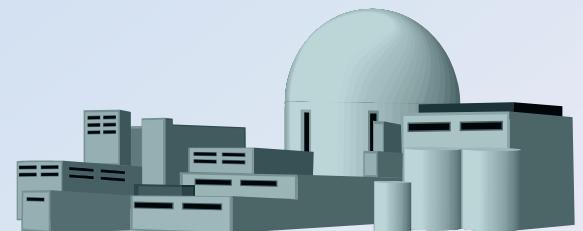


# Why Should Reactor Designers Care About Nuclear Data?

## Reactor Physics Calculations



The Shippingport Reactor (Critical in 1957)  
<http://www.pabook.libraries.psu.edu/palitmap/Shippingport.html>



- Effective neutron Multiplication factor
- Neutron flux
- Burnup
- Kinetics



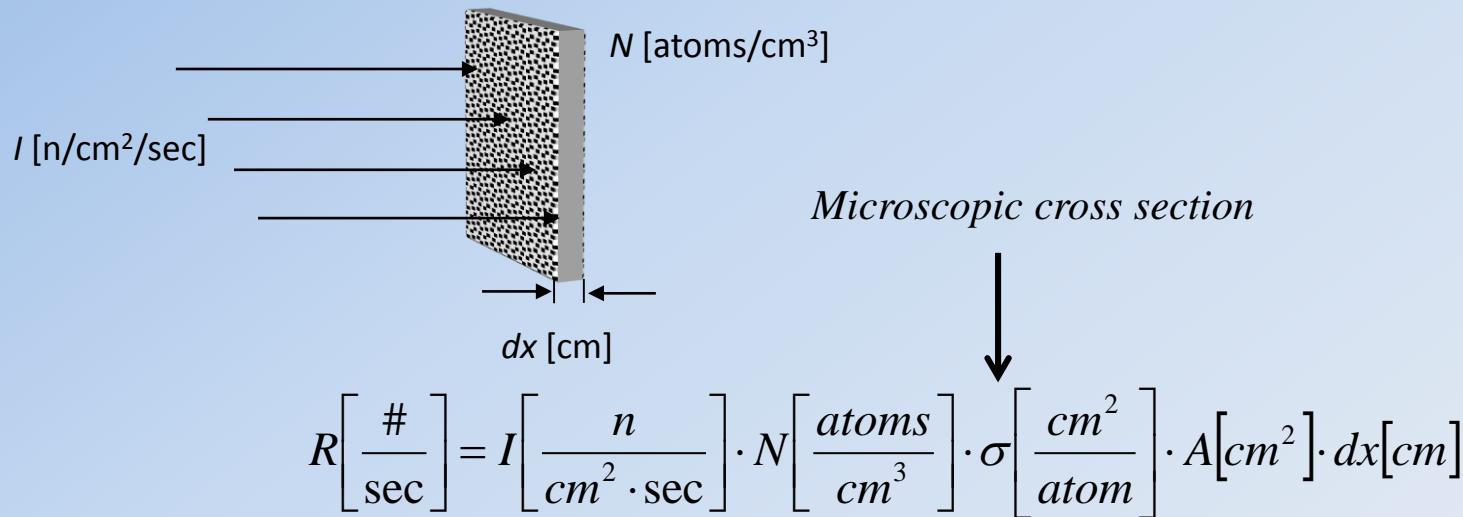
# Physics Design Limitations

- Modern computational methods are greatly improved
- Monte Carlo Methods
  - Advantages
    - Can describe the geometry at a level of a CAD drawing.
    - Includes different physics models in great detail.
    - Can solve time dependent problems.
  - Limitations
    - **Accuracy is limited by Nuclear Data and Physics models**
    - Slow for some types of calculations (but computers are getting faster)



# Nuclear Reaction Cross Section

- The cross section represents the probability for neutron interaction and is measured in units of area.

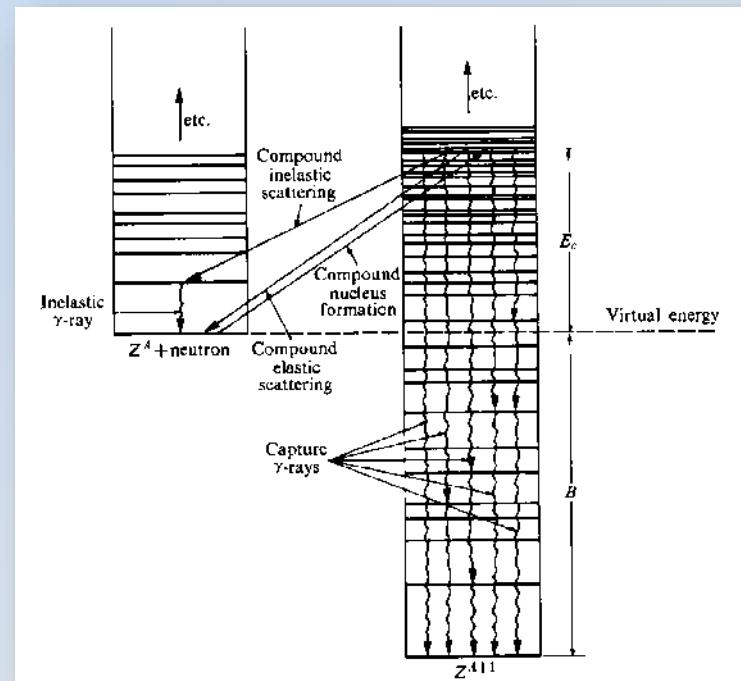
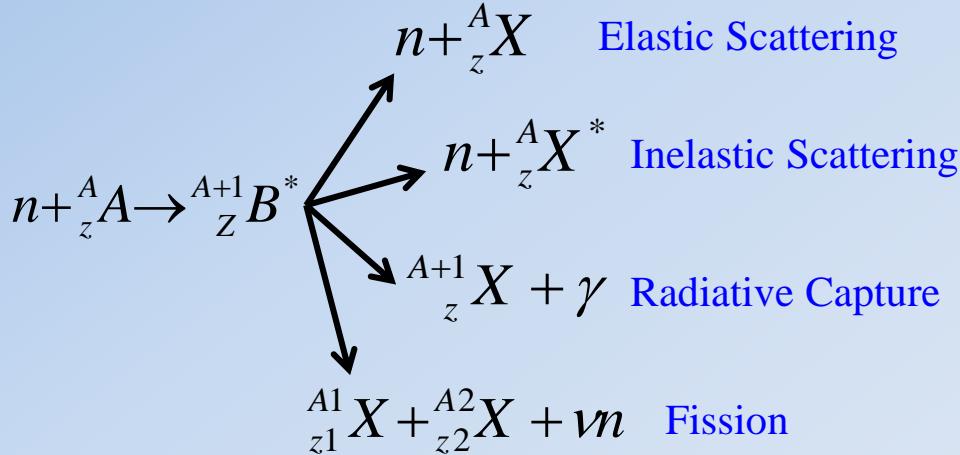


$$\text{Probability for interaction} = \frac{\text{Reaction rate}}{\text{Incident particle rate}} = \frac{IN\sigma Adx}{AI} = N\sigma dx$$



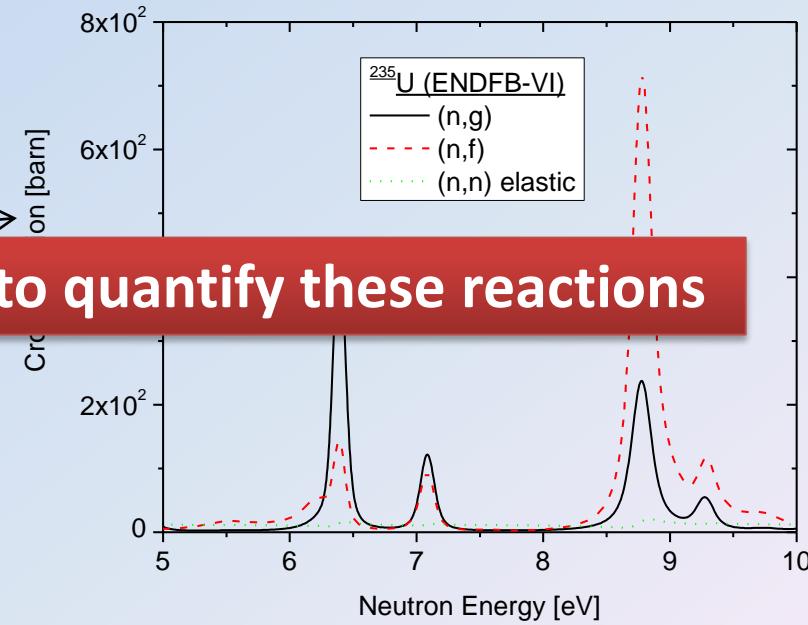
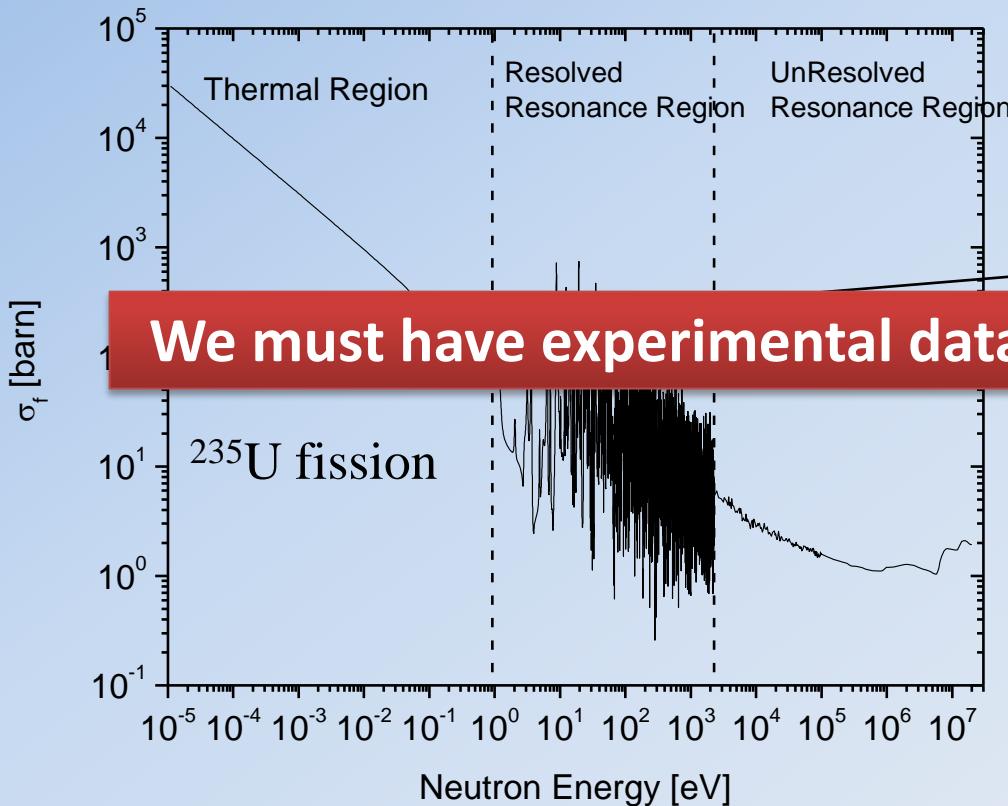
# The Concept of Compound Nucleus

- The neutron incident on a target material first creates a compound nucleus.
- The probability to form a compound nucleus increases near energy levels in the compound nucleus.
  - The magnitude of this increase is determined by the lifetime of the compound nucleus state.
  - There are several decay modes resulting in different interaction rates.

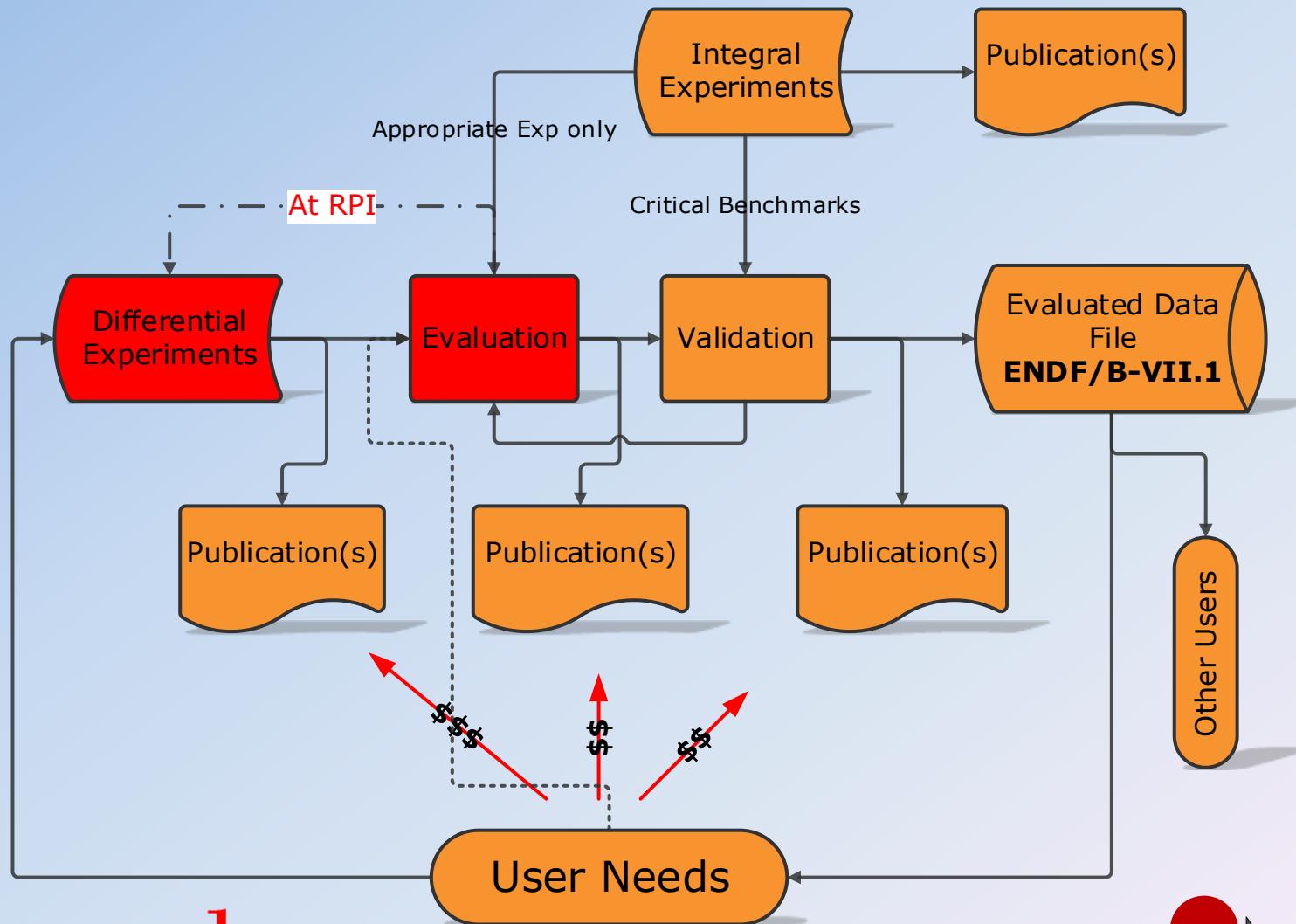


# Cross Section Energy Ranges

- Our understanding of physics is not sufficient to predict the energies of the resonances, their strength, or other quantum numbers (spin, parity, angular momentum)
- We do have a formalism to describe the shape of a resonance as a function of energy
- Statistical theories can provide some information on average quantities.

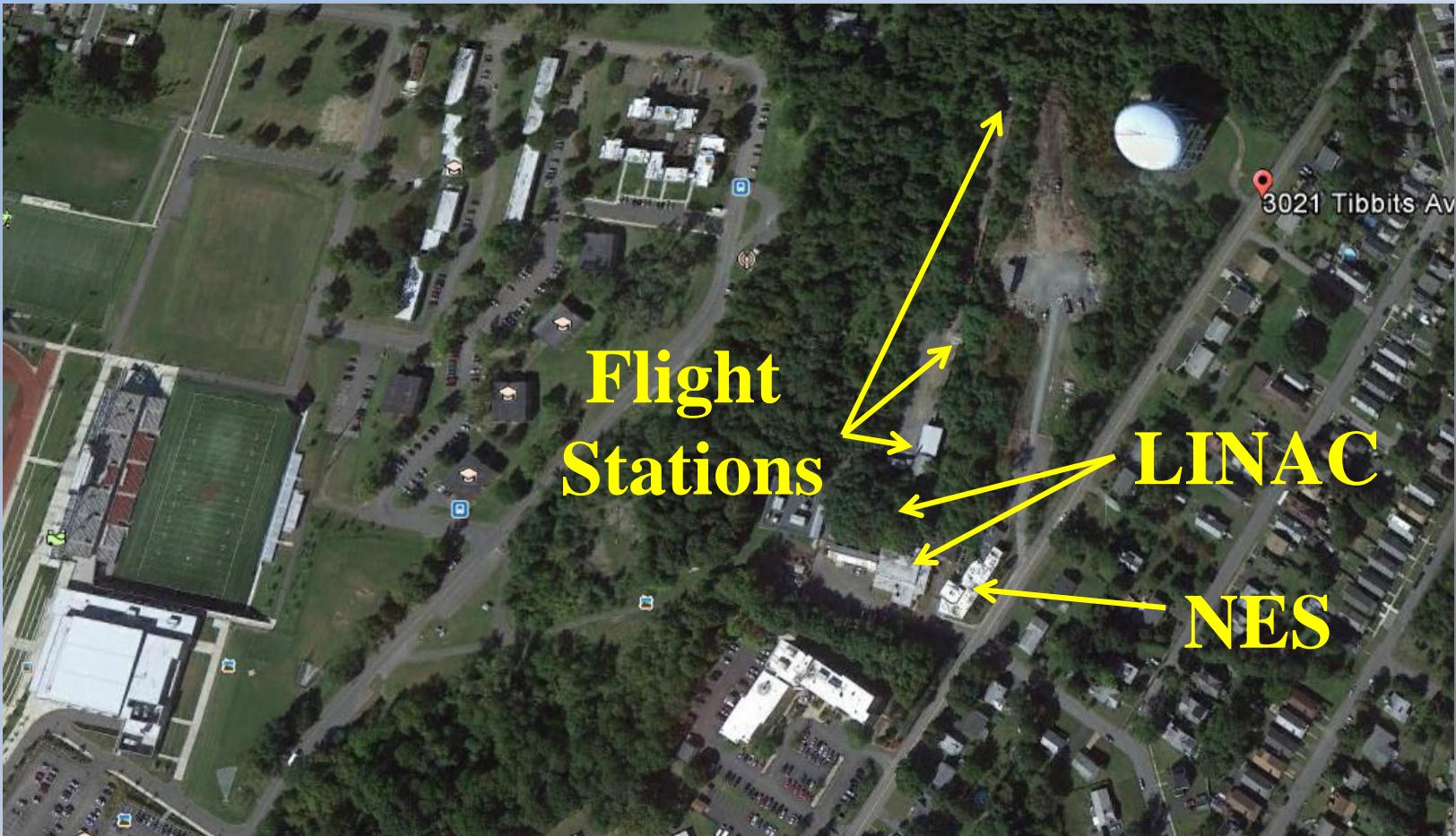


# Nuclear Data Lifecycle



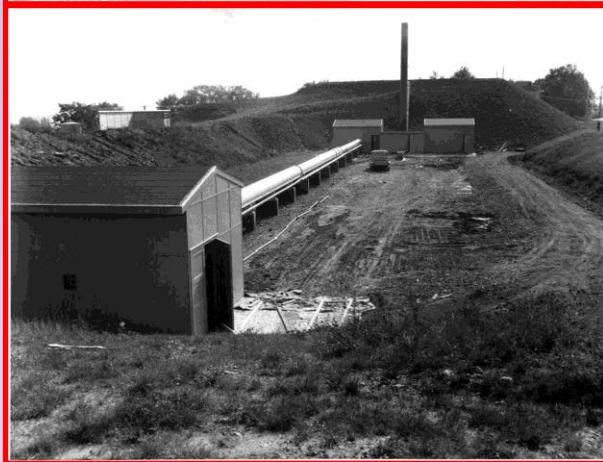
# Where is the RPI LINAC ?

- It is on the highest point in Troy, NY



# RPI LINAC History

- The RPI LINAC started operation in December 1961
- Working “continuously” since



September 1997- LINAC was designated as Nuclear Historic Landmark by the American Nuclear Society

*"This was one of the first laboratories, utilizing a high-power electron linear accelerator, that generated accurate nuclear data for the design of safe and efficient nuclear power reactors"*



Graduated over 170 students who utilized the LINAC as part of their *PhD* thesis research

*Many years of accumulated experience*

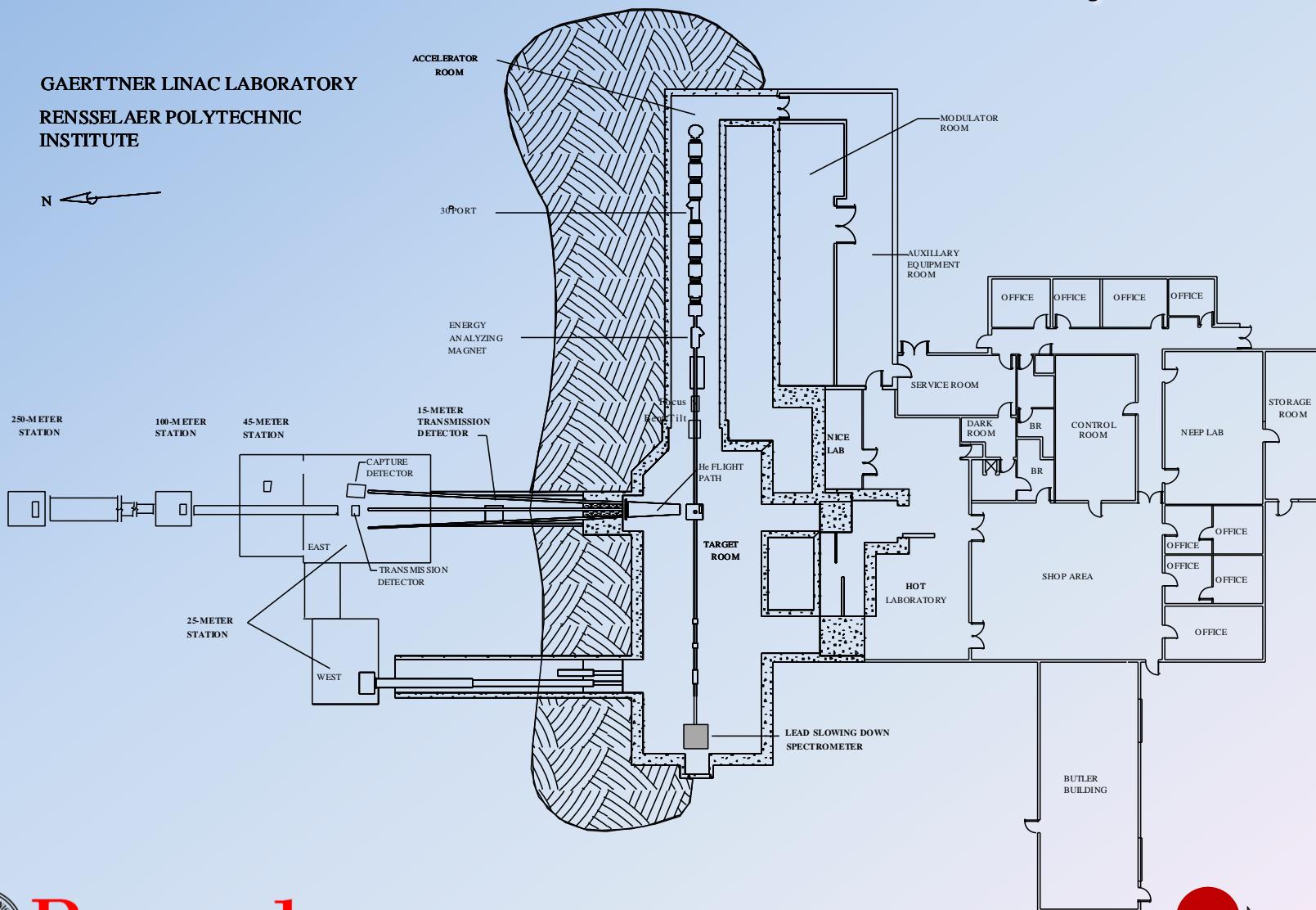


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# The RPI LINAC Facility

GAERTTNER LINAC LABORATORY  
RENNSELAER POLYTECHNIC  
INSTITUTE



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# LINAC Specifications

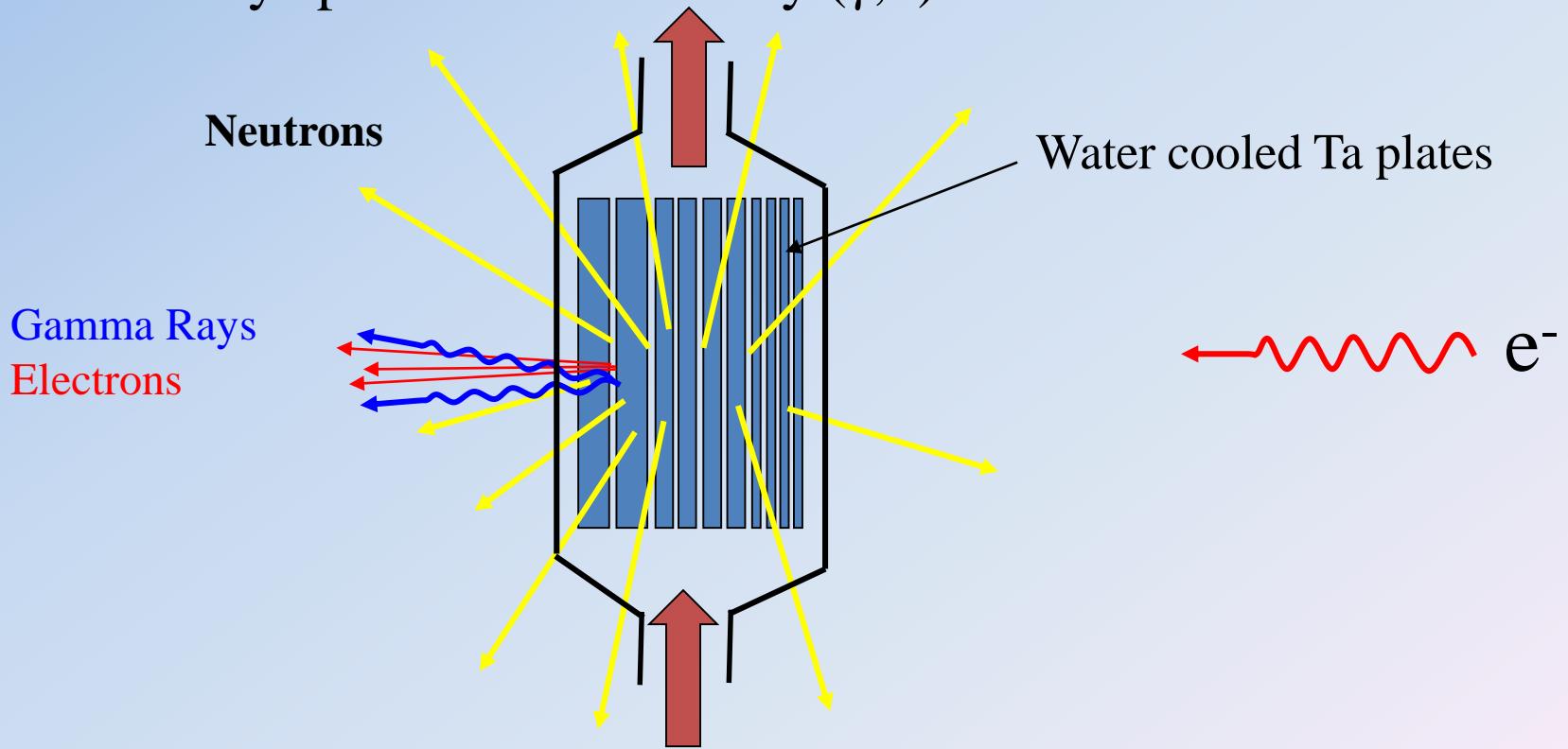
	Three Sections (Low Energy Port)	Nine Sections (High Energy Port)
<b>Electron Energy</b>	5 to 25 MeV	25 to over 60 MeV
<b>Pulse Width</b>	6 to 5000 ns	6 to 5000 ns
<b>Peak Current</b>	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)
<b>Average Power</b>	10 kw@ 17 MeV, 5000 ns	>10 kw@ 60 MeV, 5000 ns
<b>Peak Dose Rate</b>	> $10^{11}$ Rads/sec (in Silicon)	n/a
<b>Neutron Production</b>	n/a	$\sim 4 \times 10^{13}$ neutrons/sec
<b>Pulse Repetition Rate</b>	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)

- LINAC 2020 refurbishment and upgrade project is underway
- Substantial improvement in short pulse power is implemented



# Neutron Production

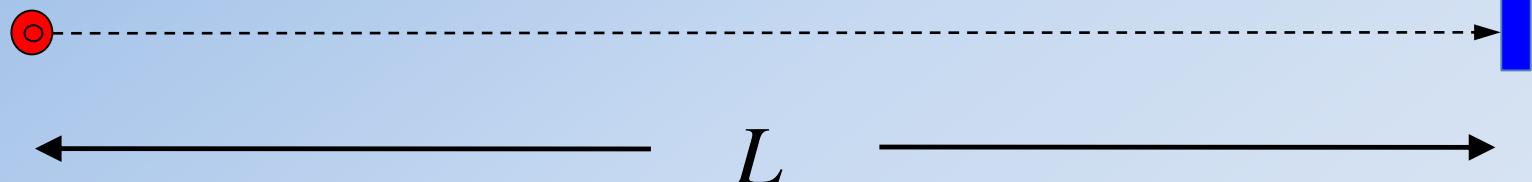
1. Bremsstrahlung X-rays are produced by stopping the electrons.
2. The X-rays produce neutrons by  $(\gamma, n)$ .



# Time of Flight (TOF)

Pulsed Neutron Source  
("White Source")

Neutron Detector



## Energy-Time relation (nonrelativistic)

$$v = \frac{L}{t} \quad , \quad E = \frac{1}{2} m \cdot v^2 \longrightarrow E = \left( \frac{K \cdot L}{t - t_0} \right)^2$$

$K$  - constant  
 $t_0$  - time zero (gamma flash)

- **Energy Resolution**

- Related to:
  - $\Delta L/L$  – moderator + detector
  - $\Delta t/t$  – LINAC electron pulse



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# Neutron Production Targets

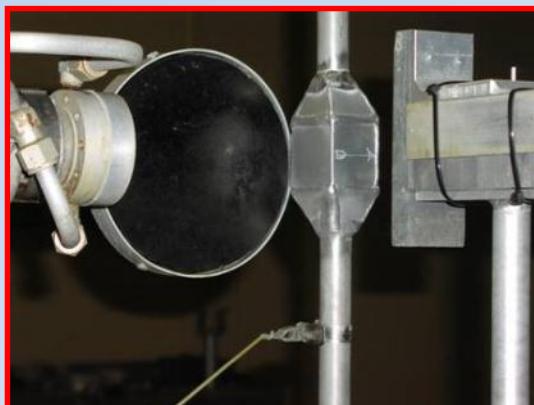
Bare Bounce Target (BBT)



Enhanced Thermal Target (ETT)



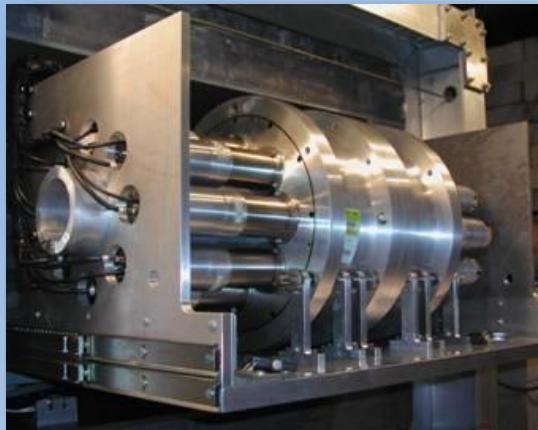
PACMAN target



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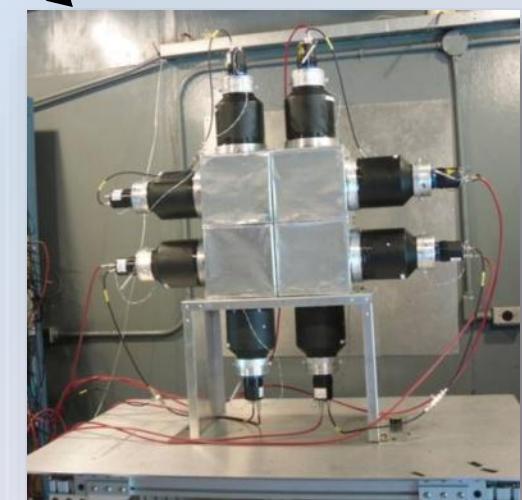
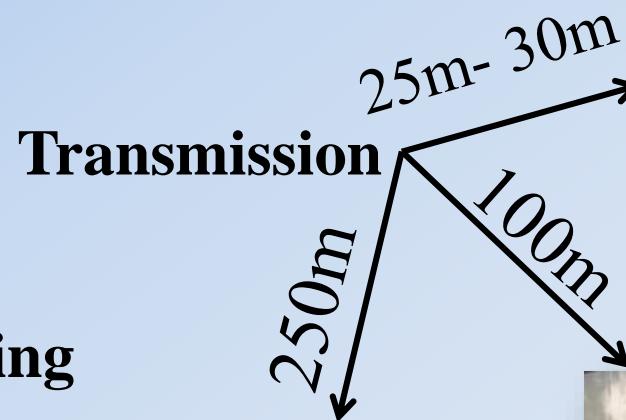
# Detectors



Capture/multiplicity  
25m



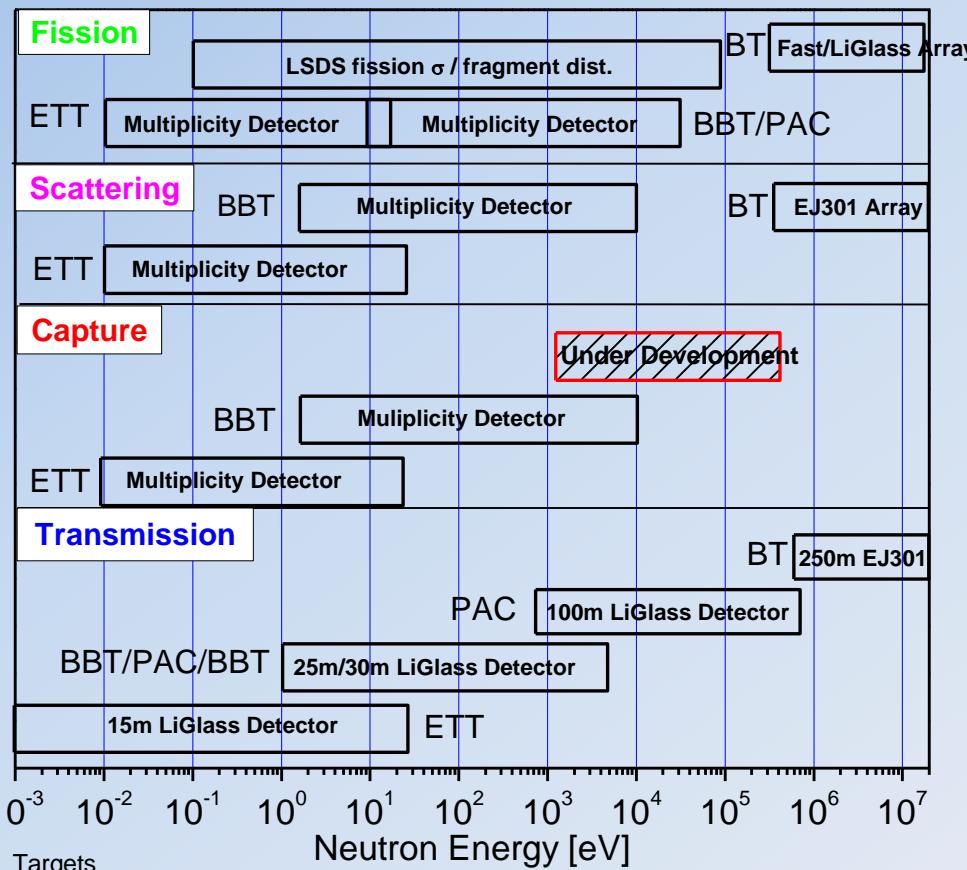
Scattering  
30m



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# RPI 2011 Capabilities Matrix

RPI LINAC - Nuclear Data Measurement Capabilities 2012



# Current Activity

- **Time of flight measurements**

- Resonance Region
  - Capture (0.01 eV – 2 keV)
  - Transmission (0.001 eV – 100 KeV)
  - Capture to fission ratio (alpha)
  - Development of a mid energy capture detector
- High energy (0.4-20MeV)
  - Scattering (30 m flight path)
  - Transmission (100m and 250m flight path)
  - Fission spectra and nubar
- High accuracy total cross section measurements using filtered beam



- **Lead Slowing Down Spectrometer**

- Simultaneous measurement of fission cross sections and fission fragment mass and energy distributions using the RPI lead slowing down spectrometer
- Measurements of energy dependent ( $n,p$ ) and ( $n,\alpha$ ) cross sections of nanogram quantities of short-lived isotopes. (collaboration with LANL).

- **Other**

- Novel quasi-monoenergetic x-ray generation
- Medical isotope production
- $S(\alpha,\beta)$  measurements (at SNS in ORNL)



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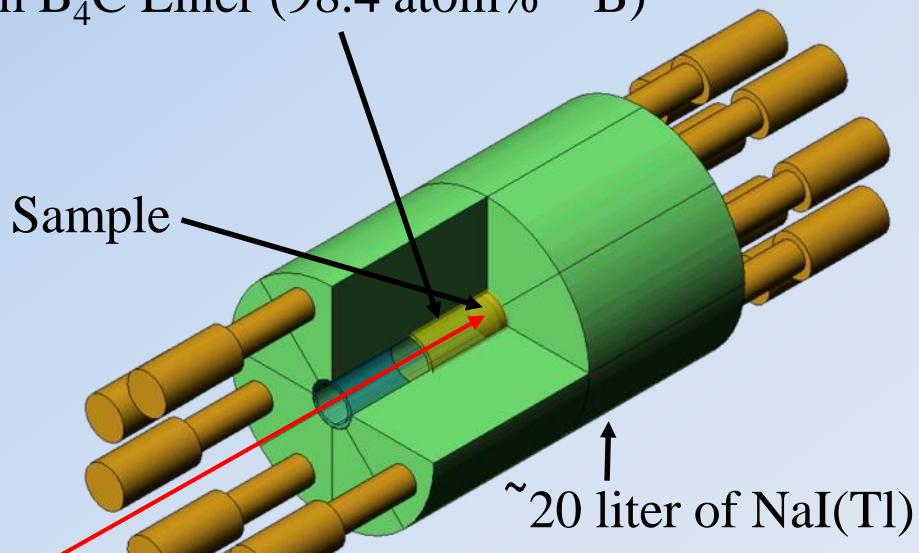
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# Resonance Region Detectors

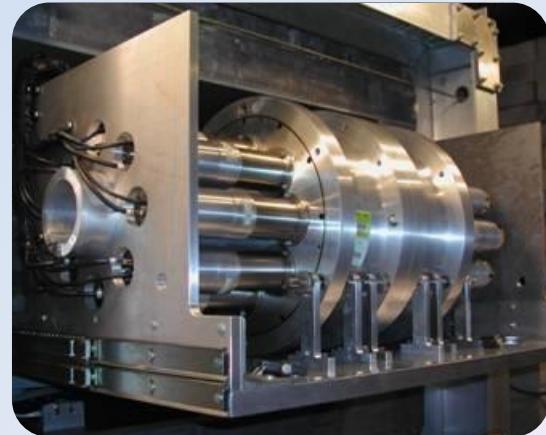
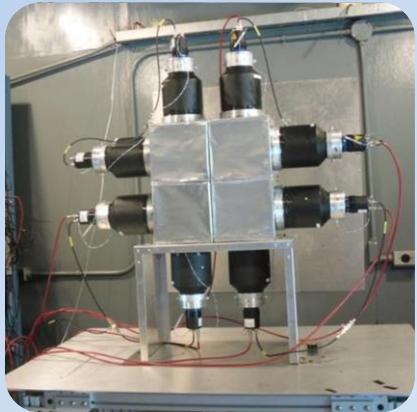
Li-Glass Detector at 25m



2 cm  $B_4C$  Liner (98.4 atom%  $^{10}B$ )



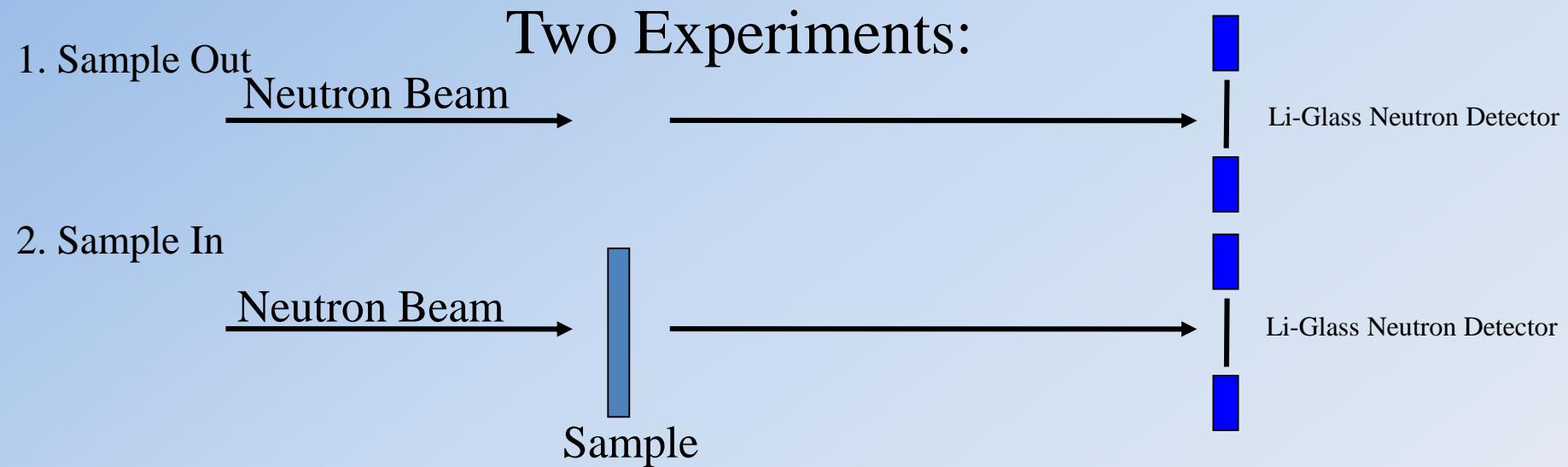
Li-Glass Detector at 100m



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# Transmission Experiment



$$T = \frac{C_{\text{Sample In}}}{C_{\text{Sample Out}}} = \exp(-N\sigma_t)$$

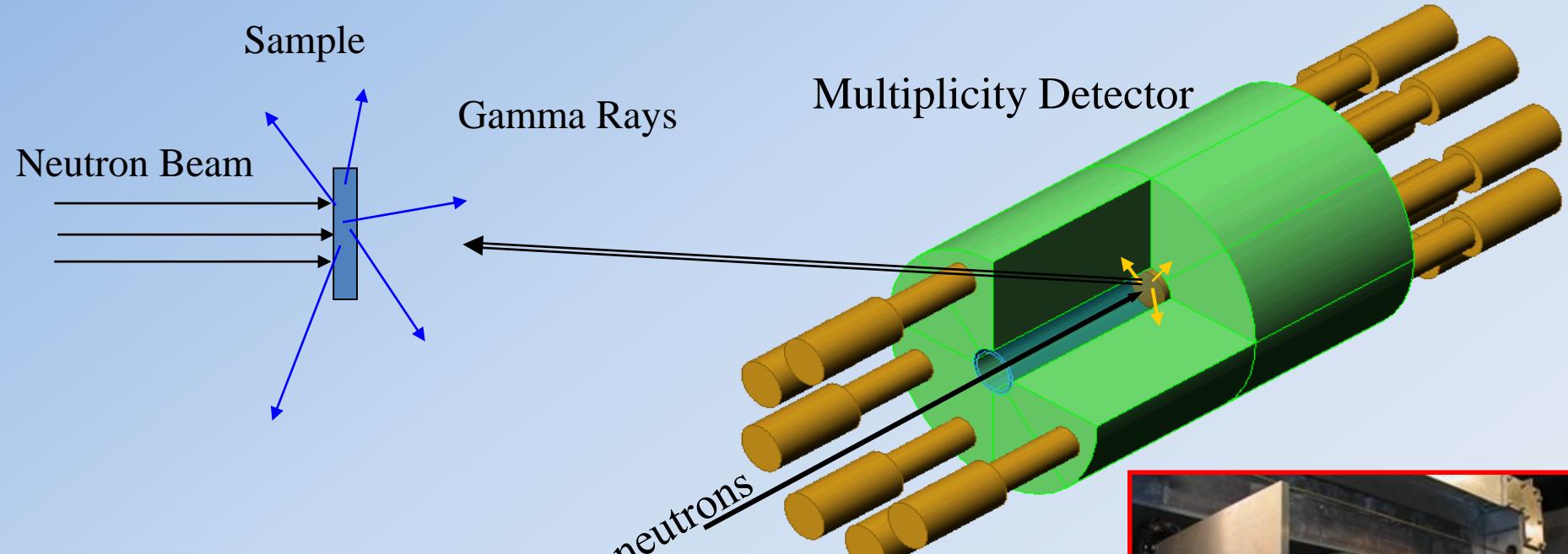
$N$  – Number density [atoms/barn]

$\sigma_t$  – Total cross section



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# Capture Experiments



The capture Yield:

$\phi$  – neutron flux

$\eta$  – detection efficiency

$$Counts = \phi Y \eta$$

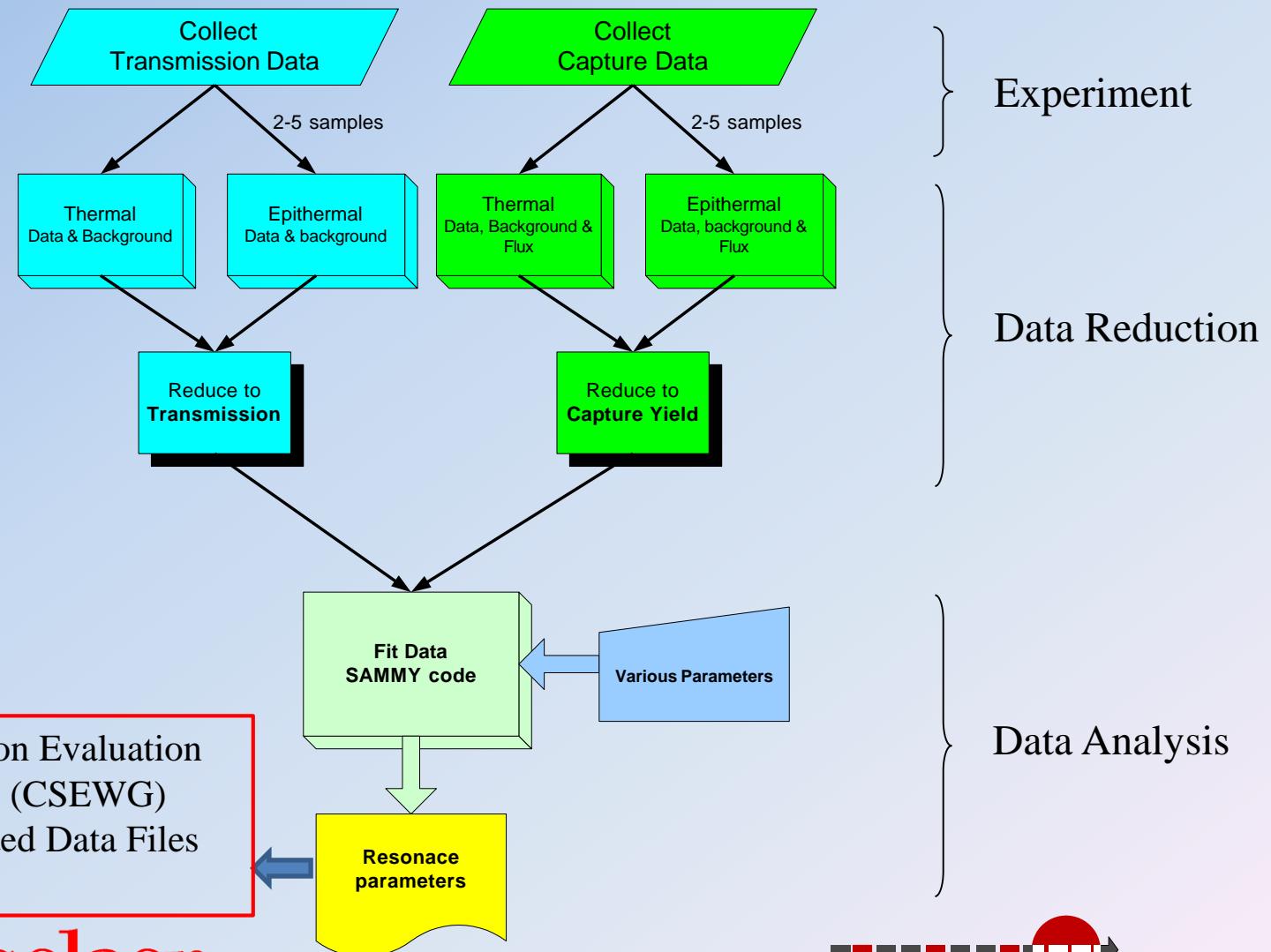
$$Y = (1 - \exp(-N\sigma_t)) \frac{\sigma_\gamma}{\sigma_t}$$



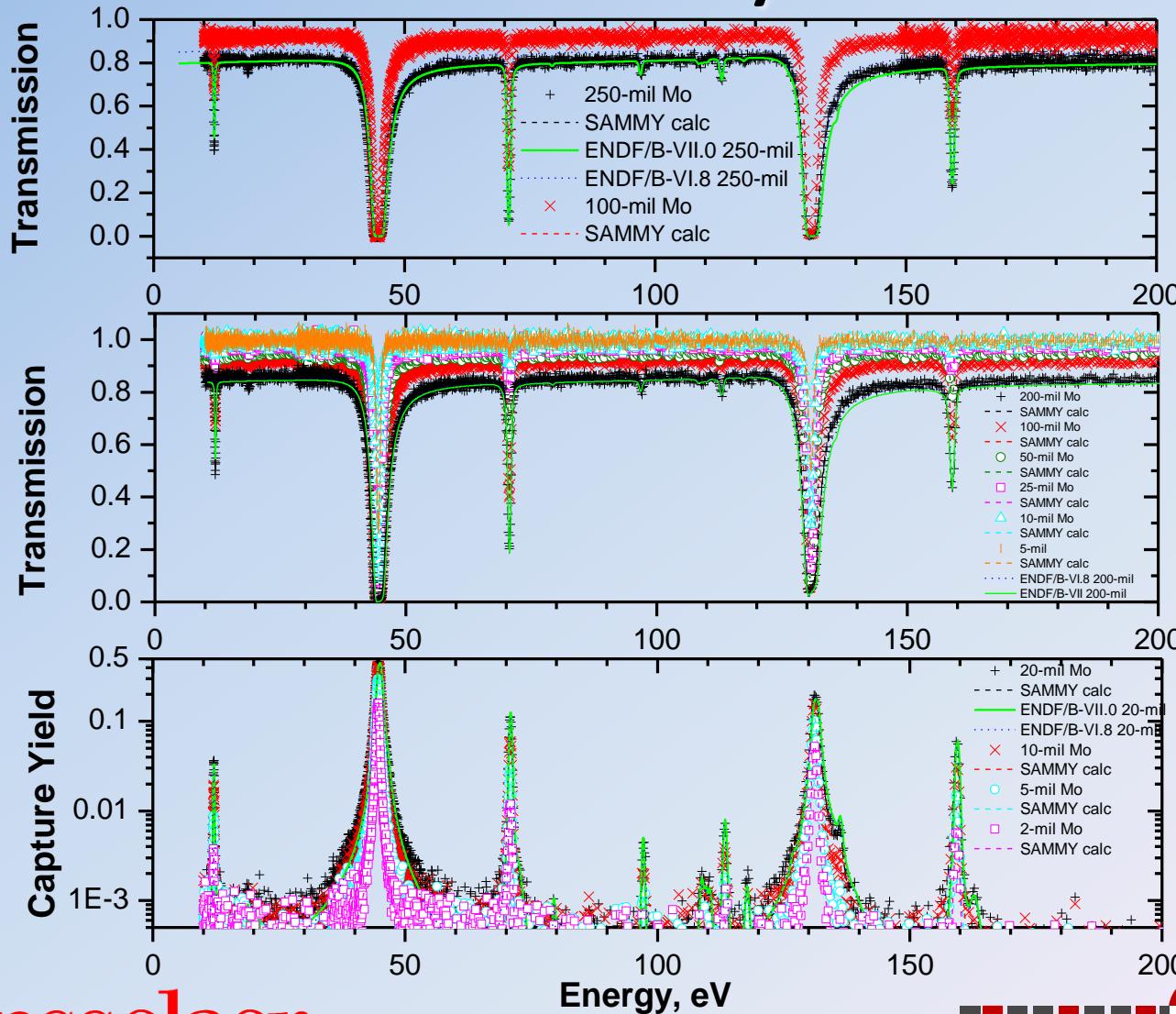
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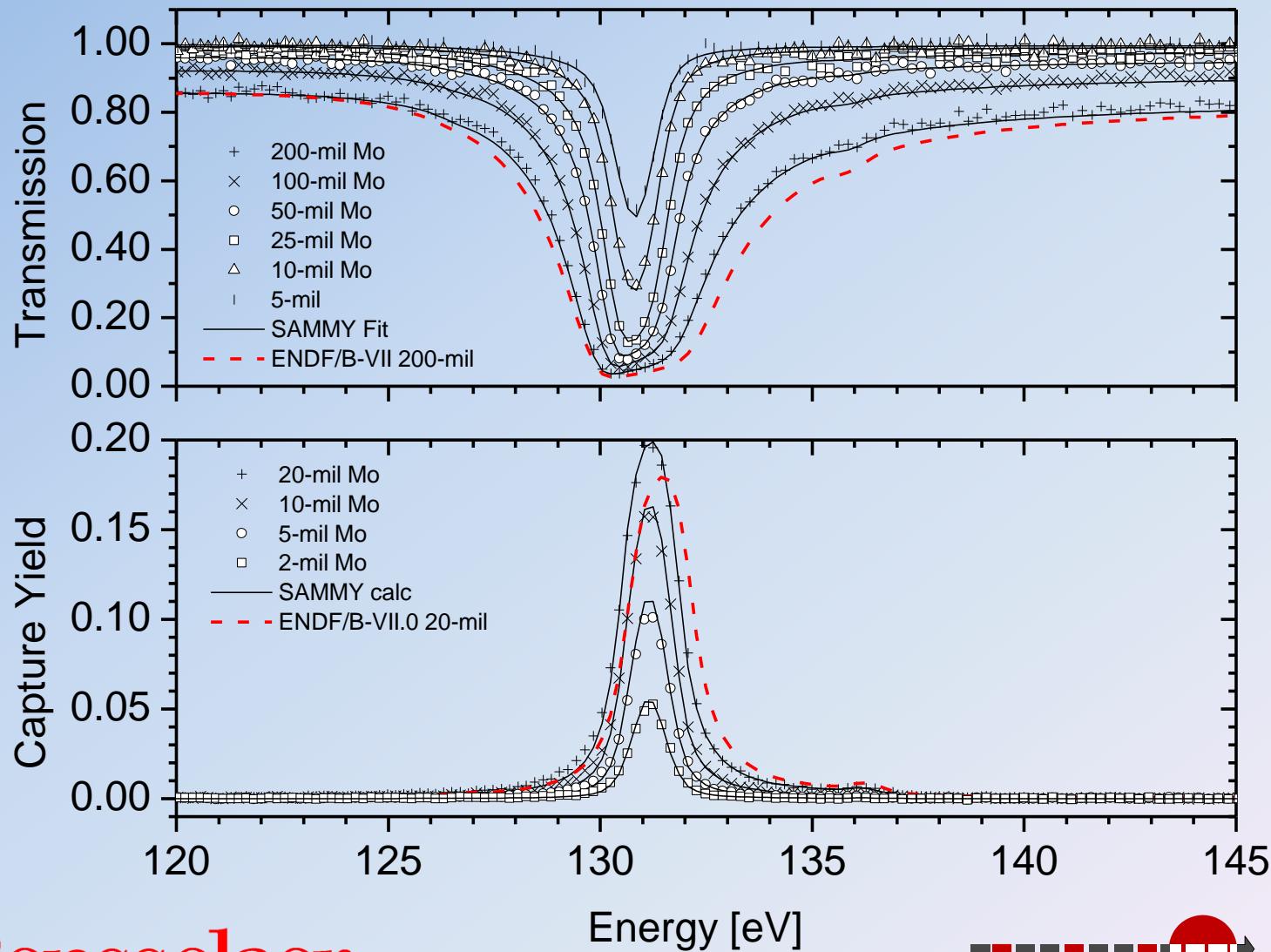
# Resonance Cross Section Measurements and Data Analysis



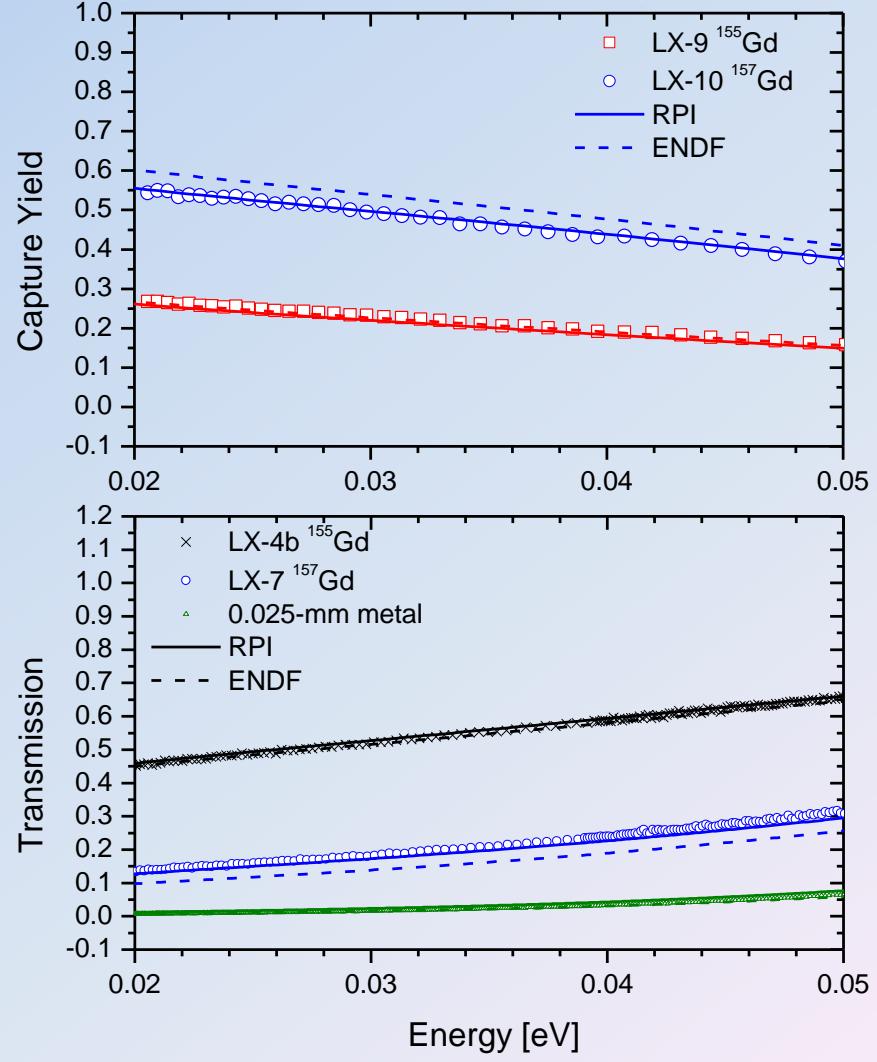
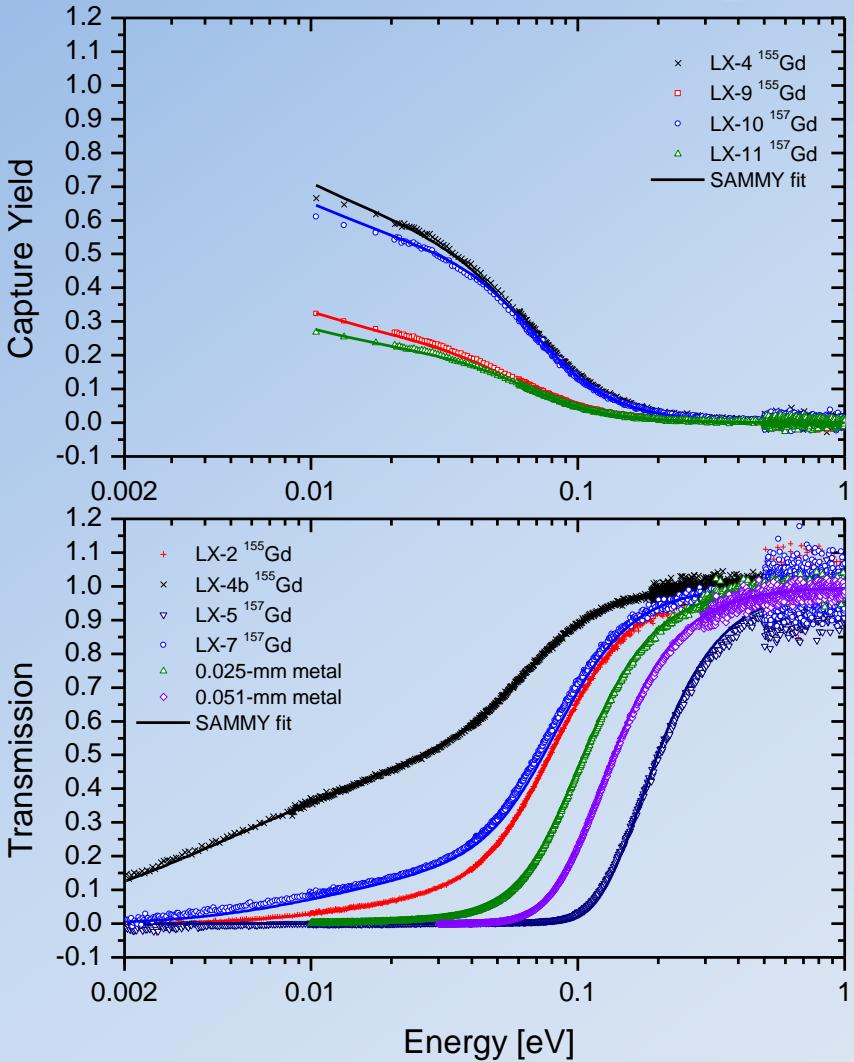
# Elemental Molybdenum



# Elemental Molybdenum 120 eV - 145 eV



# Gd Thermal Region - Separated Isotopes



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# Are We Improving Reactor Calculations ?

cea

## Feedback of the new RPI Gd resonance parameters set on FUBILA Full MOX poisoned core calculation

P. Blaise – O. Litaize  
Reactor Physics and Cycle Service (SPRC\LEPh)

*correcting the overpredictions previously reported in the clustered gadolinium pins. Earlier reported discrepancies observed in PROTEUS integral experiments, between measured and calculated reaction rates in the gadolinium-poisoned pins, might thus be due to inaccurate gadolinium cross sections. The PROTEUS results support the new thermal and epithermal gadolinium data measured by Leinweber et al.*

NUCLEAR SCIENCE AND ENGINEERING: 163, 17–25 (2009)

## Impact of New Gadolinium Cross Sections on Reaction Rate Distributions in 10 × 10 BWR Assemblies

G. Perret,\* M. F. Murphy, and F. Jatuff†

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

J-Ch. Sublet and O. Boulard

Commissariat à l'Energie Atomique, DEN, Cadarache, 13108 St Paul lez Durance, France

and

R. Chawla

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland  
and

École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Received July 28, 2008

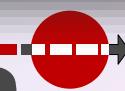
Accepted October 28, 2009

on ( $C_g/F_{tot}$ )  
OTEUS pro-  
measured  
ratios were  
e effort was  
out success.  
Leinweber

et al. and differed significantly from current library values. ENDFTB-VILO gadolinium cross sections have currently been modified to include the new measurements, and these data have been processed with NJOY to yield files usable by MCNPX. Fission rates in the gadolinium-poisoned fuel pins of the SVEA-96 Optima2 pins were increased by 1.4 to 2.0% using the newly produced cross sections, yielding to a better agreement with the experimental values. Predicted  $C_g/F_{tot}$  ratios were decreased on average by 1.7% in both clustered and unclustered groups of gadolinium-poisoned fuel pins of the SVEA-96+ assembly correcting the overpredictions previously reported in the clustered gadolinium pins. Earlier reported discrepancies observed in PROTEUS integral experiments, between measured and calculated reaction rates in the gadolinium-poisoned pins, might thus be due to inaccurate gadolinium cross sections. The PROTEUS results support the new thermal and epithermal gadolinium data measured by Leinweber et al.

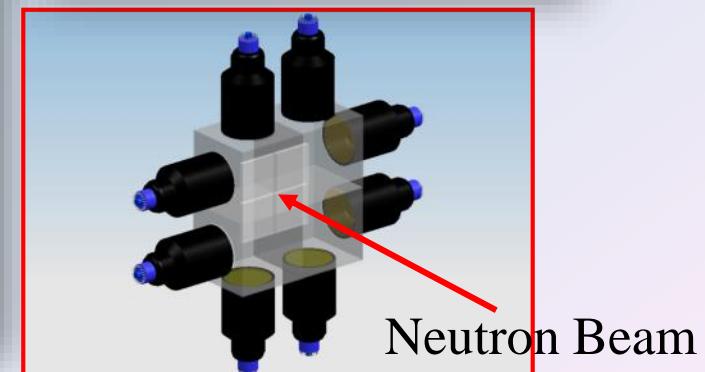
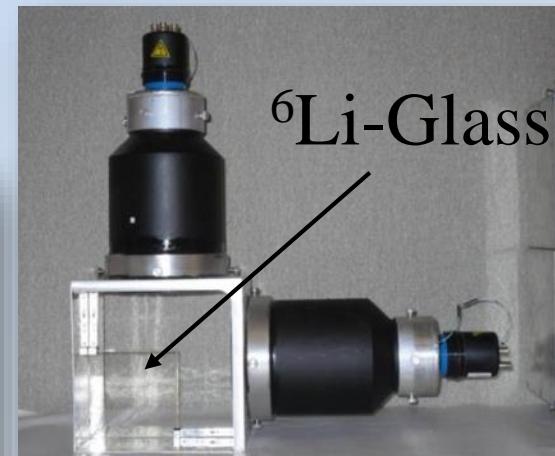
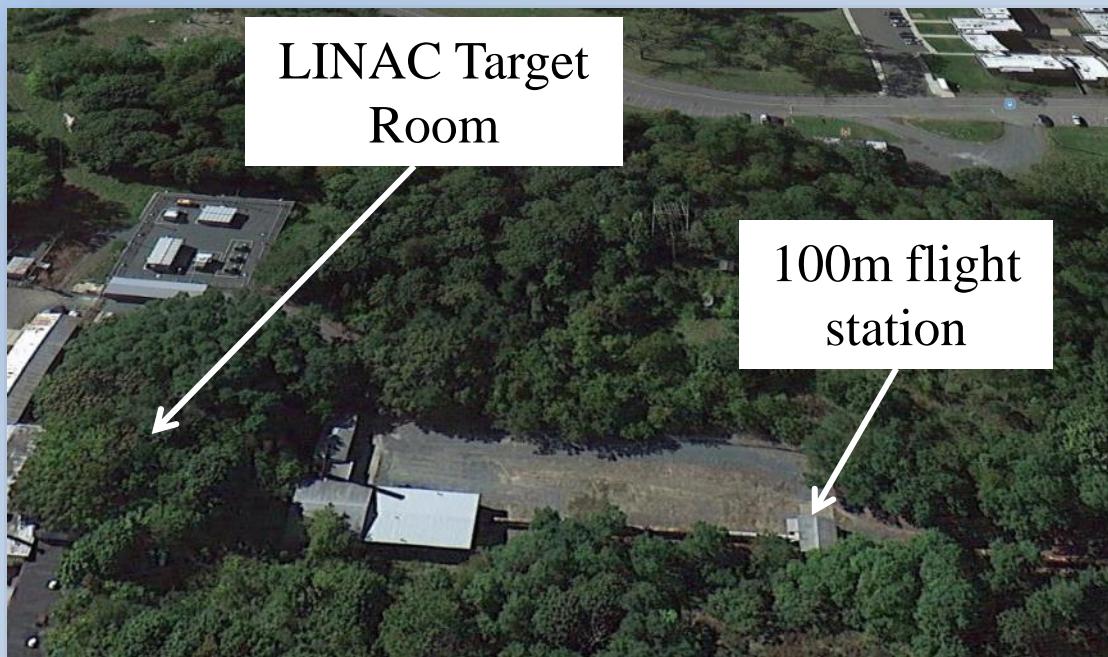


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# High Resolution Transmission Detector

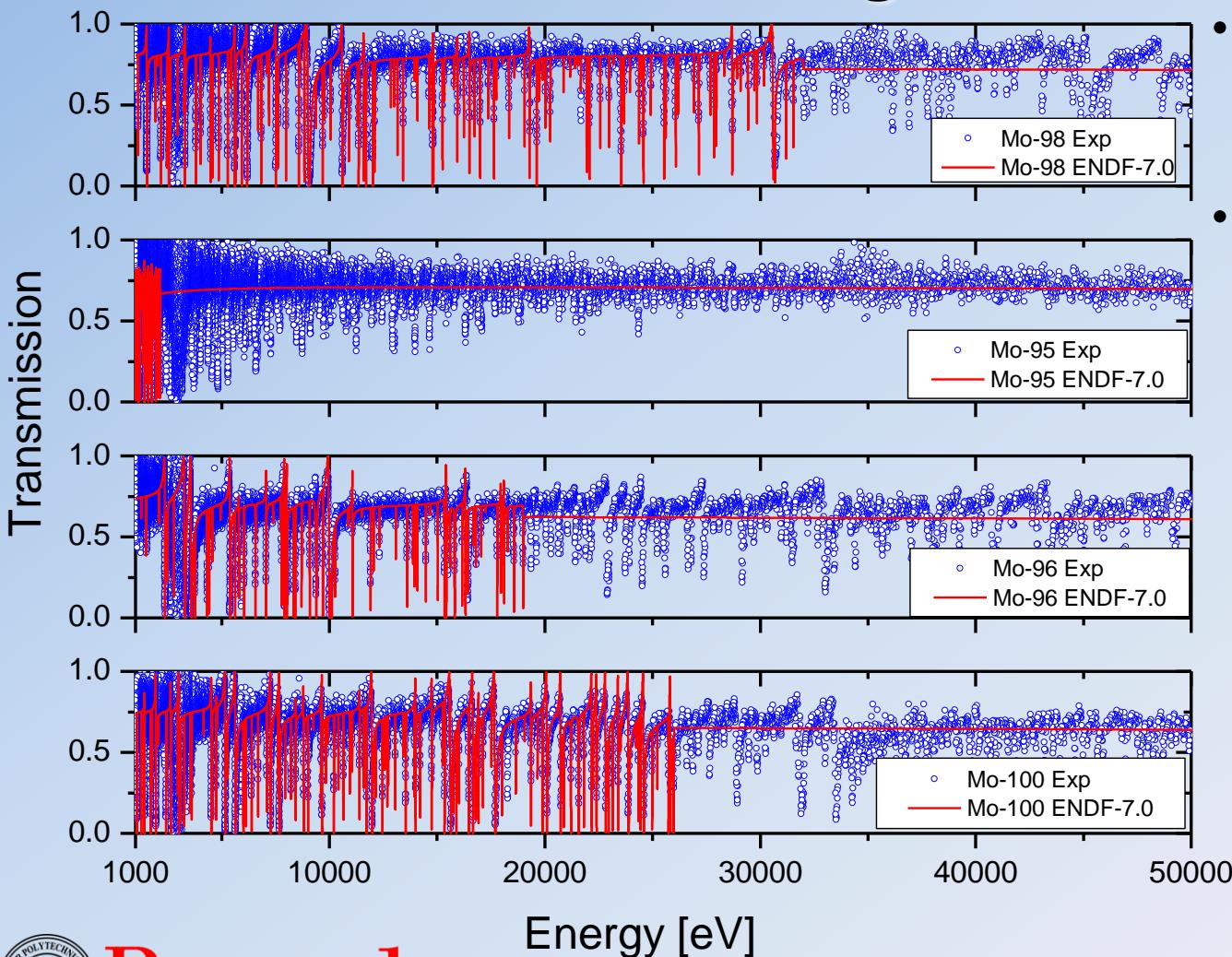
- Modular Li-Glass detector at 100m flight path
  - Extends our capabilities to the unresolved resonance region
  - Measurement of  $^{95,96,98,100}\text{Mo}$  completed.



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# Mo Isotopes in the Resonance Region

## 100m Flight Path



- Resonance parameters analysis in progress
- Data provide information to extend the resolved resonance region of several isotopes



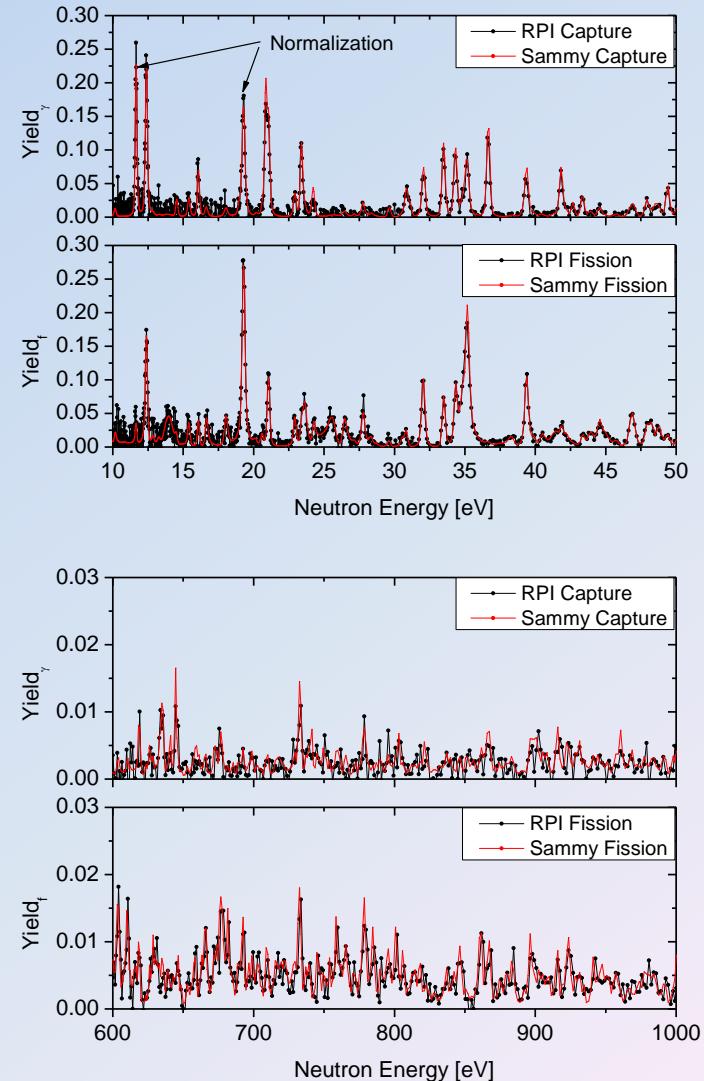
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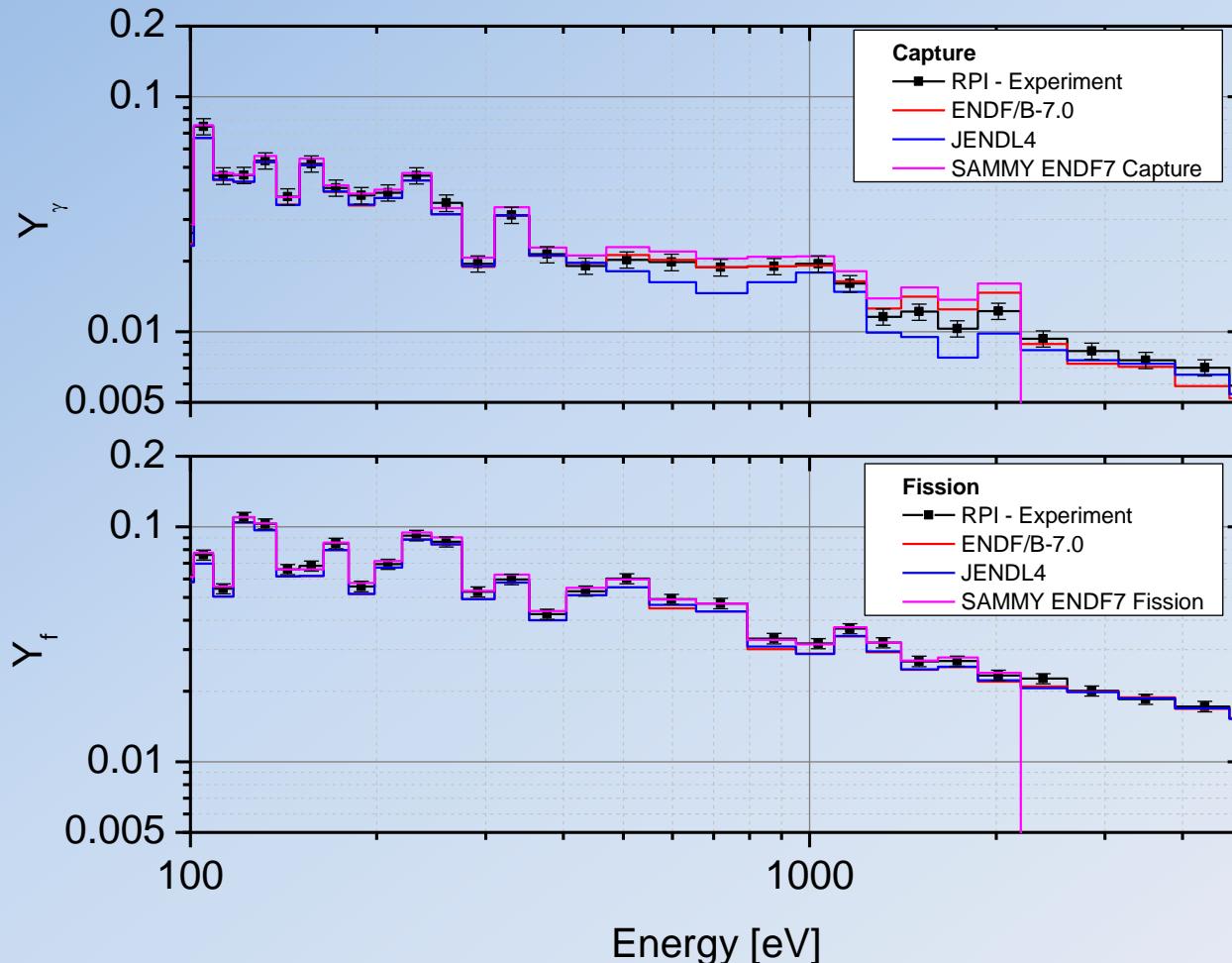
# $^{235}\text{U}$ Capture & Fission Yield Data - Epithermal Measurement

- Challenges:
  - Normalization
  - False capture due to neutron scattering
- Normalize experimental fission yield to resonance
  - $Y_f^{\text{ENDF}} = k_1 \cdot Y_f$       Solve for  $k_1$  @ 19.3 eV res  $\left(\frac{\Gamma_f}{\Gamma} = 0.63\right)$
  - Use two equations for predominantly capture and fission resonances
    - @ 11.7 eV res  $\left(\frac{\Gamma_\gamma}{\Gamma} = 0.86\right)$
    - @ 19.3 eV res  $\left(\frac{\Gamma_f}{\Gamma} = 0.63\right)$
- $Y1_\gamma^{\text{ENDF}} = k_2 \cdot Y1_\gamma - k_3 \cdot k_1 \cdot Y1_f$
- $Y2_\gamma^{\text{ENDF}} = k_2 \cdot Y2_\gamma - k_3 \cdot k_1 \cdot Y2_f$
- Solve the two equations for  $k_2$  and  $k_3$
- Need 2 resonances with known parameters ◀

Provides data to address WPEC subgroup 29 report  
“Uranium-235 Capture Cross-section in the keV to MeV Energy Region”



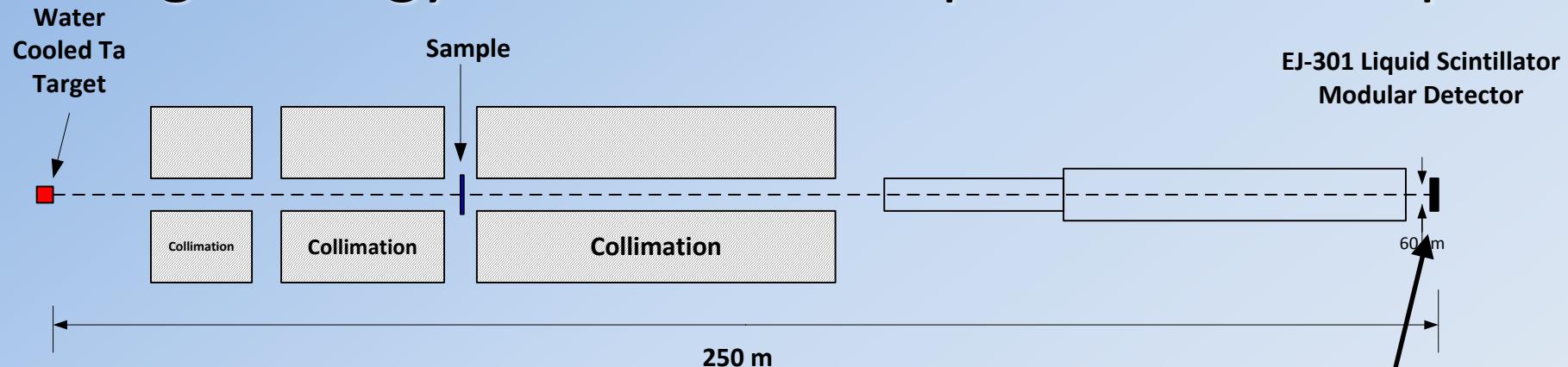
# Comparing $^{235}\text{U}$ Fission and Capture with Evaluations



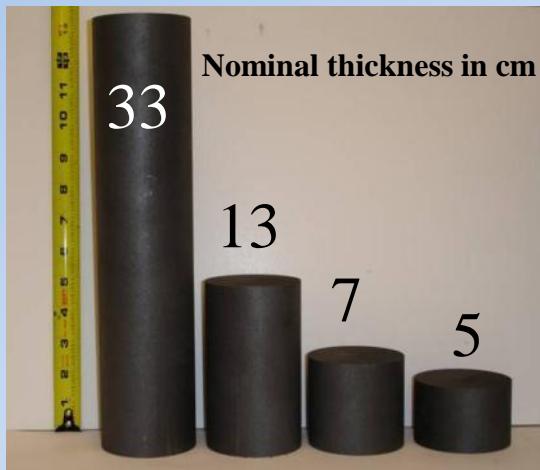
- Fission is in excellent agreement with evaluations
- Capture data has up to 8% multiple scattering that must be taken into account during the analysis
- Capture error is about 8%
- **0.4-1 keV capture data is closer to ENDF/B-7.0**
- **1-2 keV ENDF/B7.0 too high JENDL 4.0 too low.**
- **E>1 keV data is slightly higher than evaluations but within errors.**



# High Energy Transmission Experimental Setup



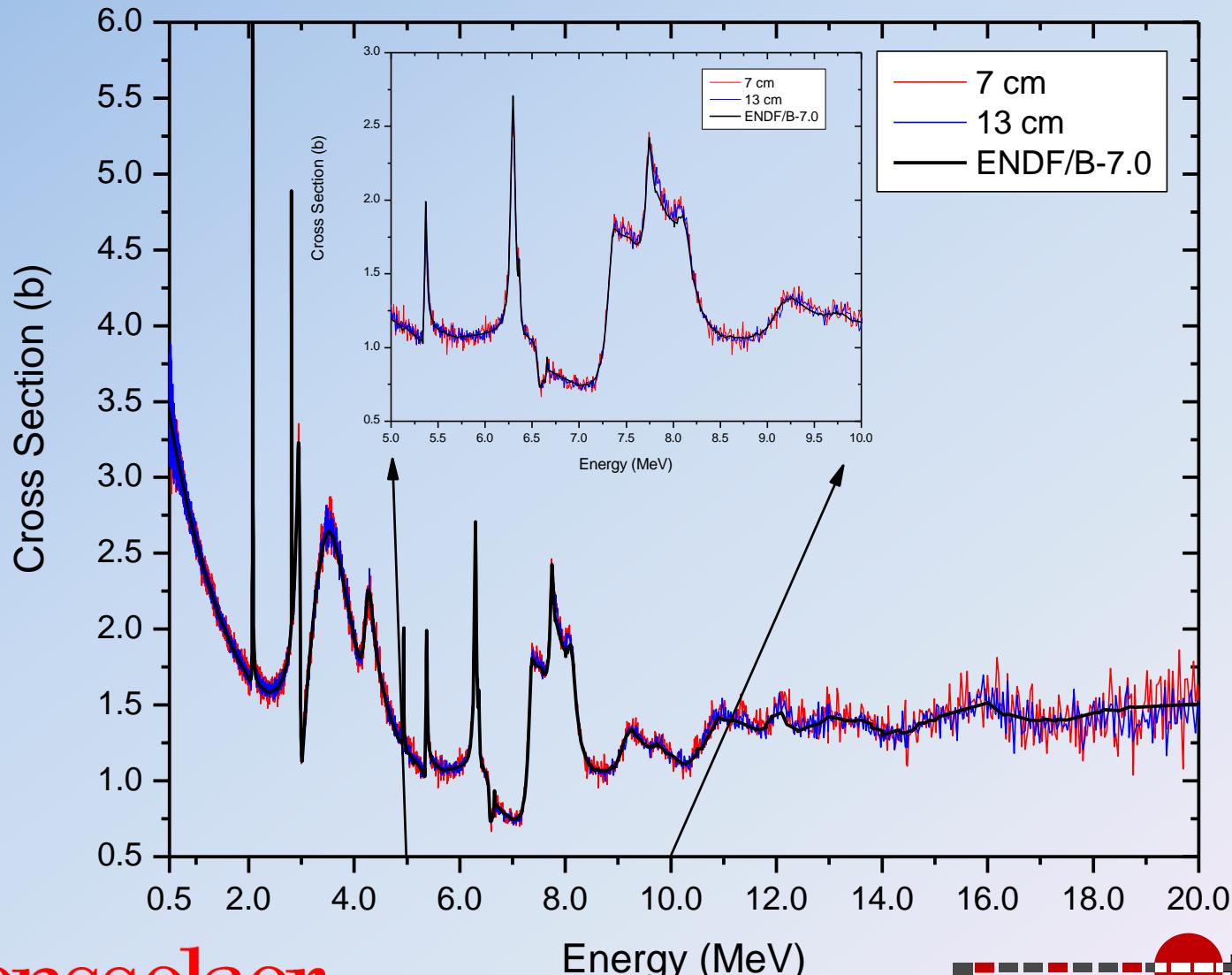
## Graphite Samples



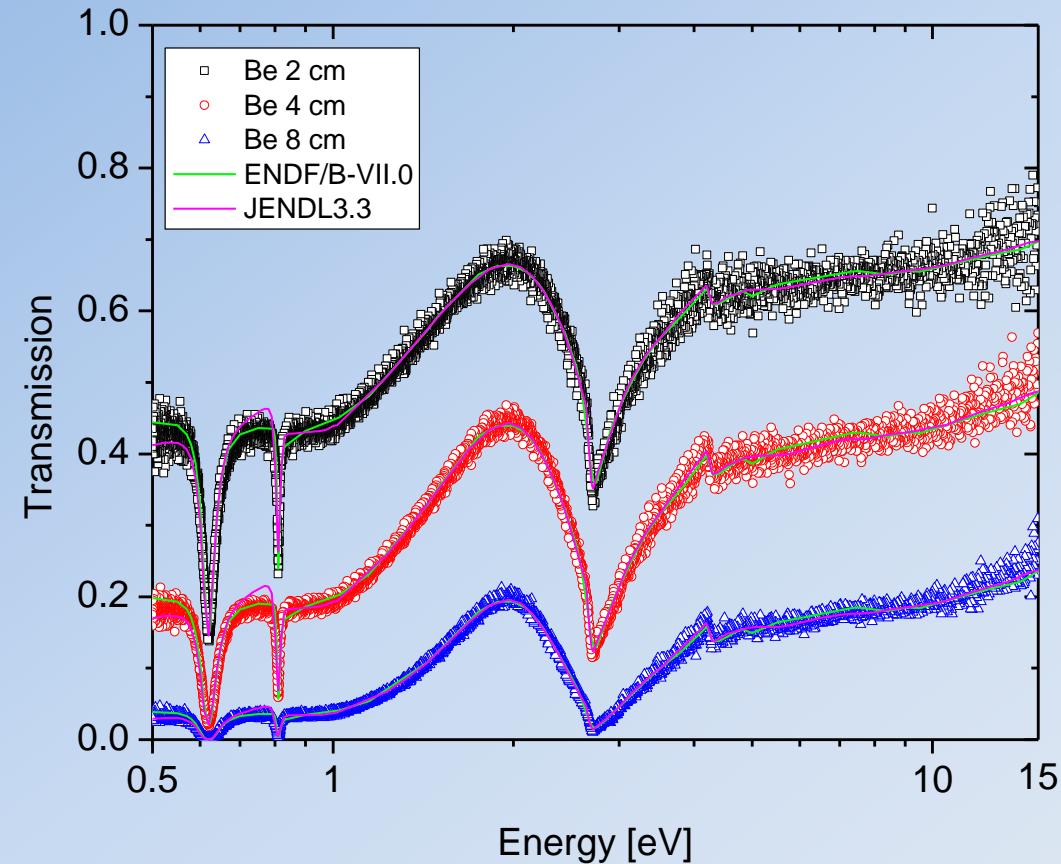
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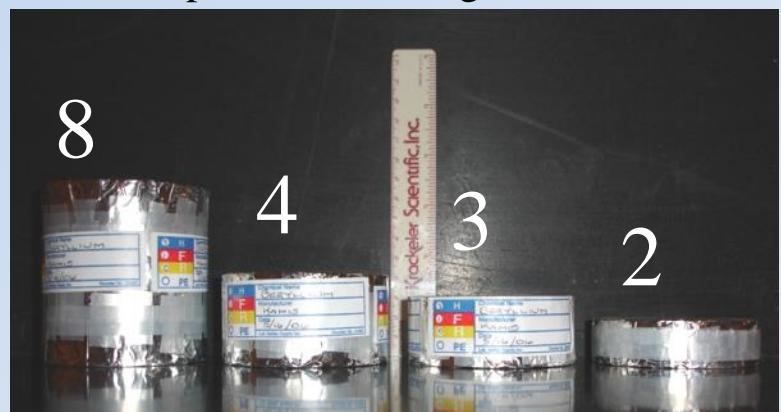
# Results – Carbon Total Cross Section



# Beryllium Transmission



Beryllium samples  
Sample thickness is given in cm

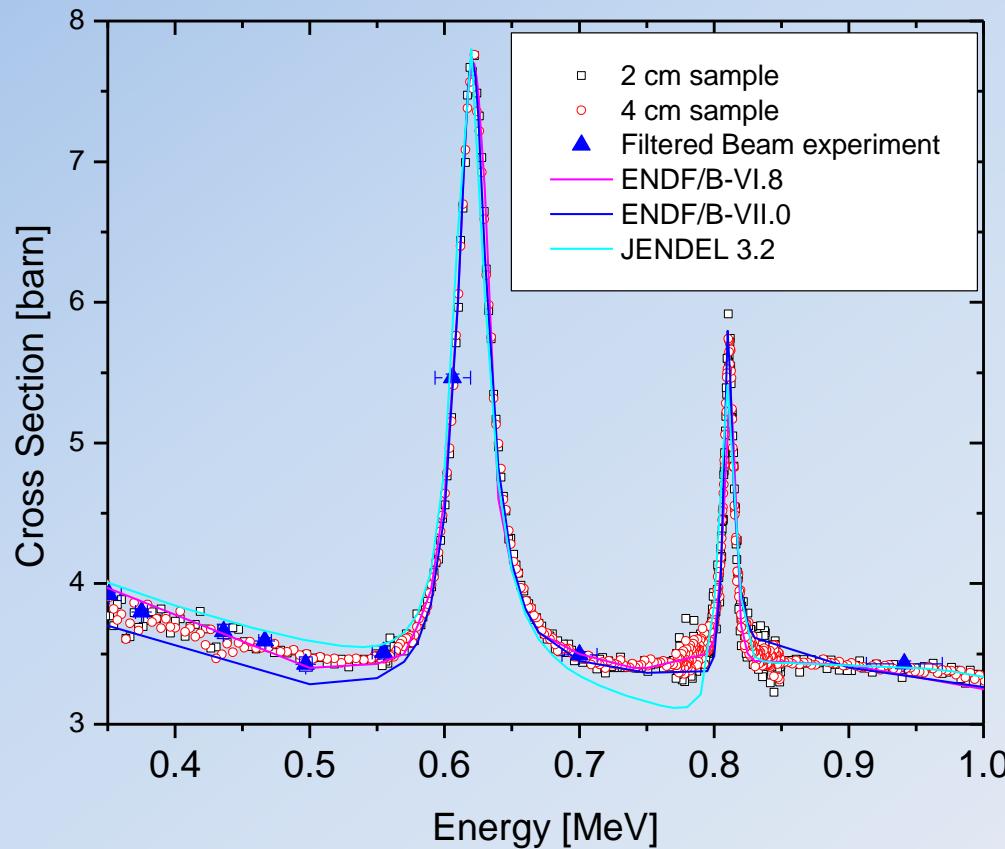


Reconfigured the detector with two units to reduce background



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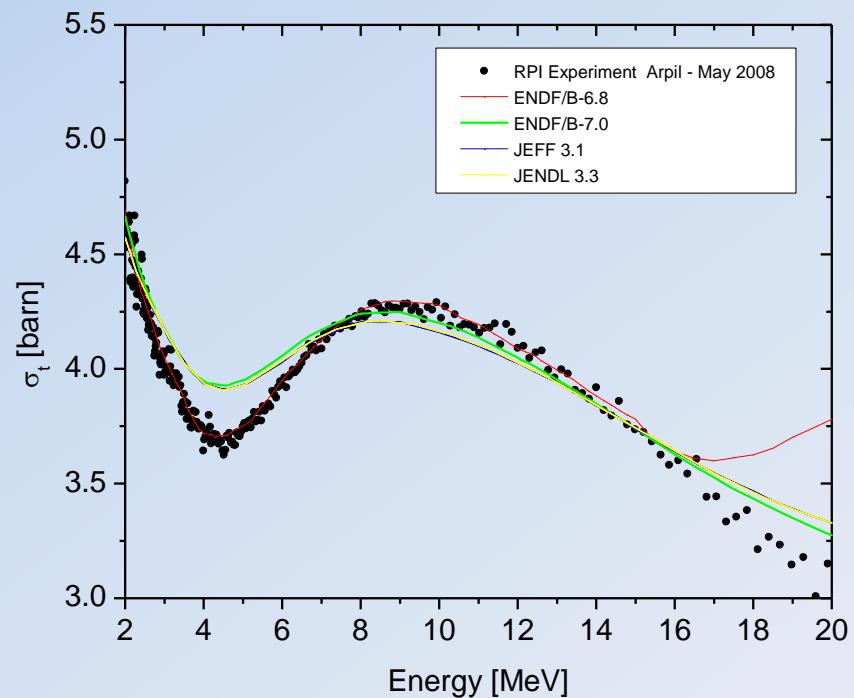
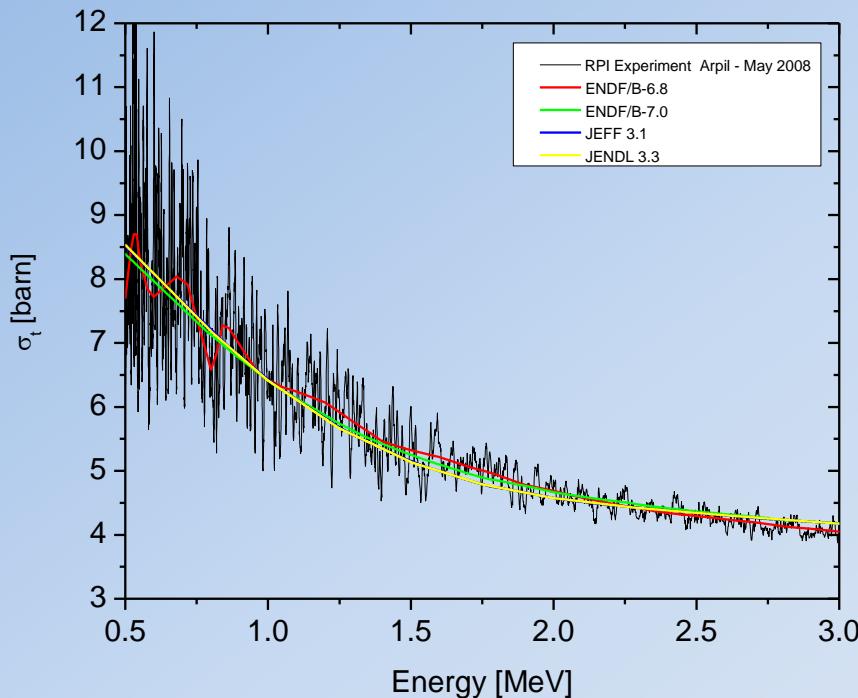
# Beryllium Total Cross Section (Low Energy)



M.J. Rapp, Y. Danon, F.J. Saglime, R.M. Bahran and D.G. Williams, G. Leinweber, D.P. Barry and R.C. Block, "Beryllium and Graphite Neutron Total Cross Section Measurements from 0.4 to 20 MeV", Nuclear Science and Engineering, Vol. 172, No. 3. Pages 268-277, November 2012 (2012).



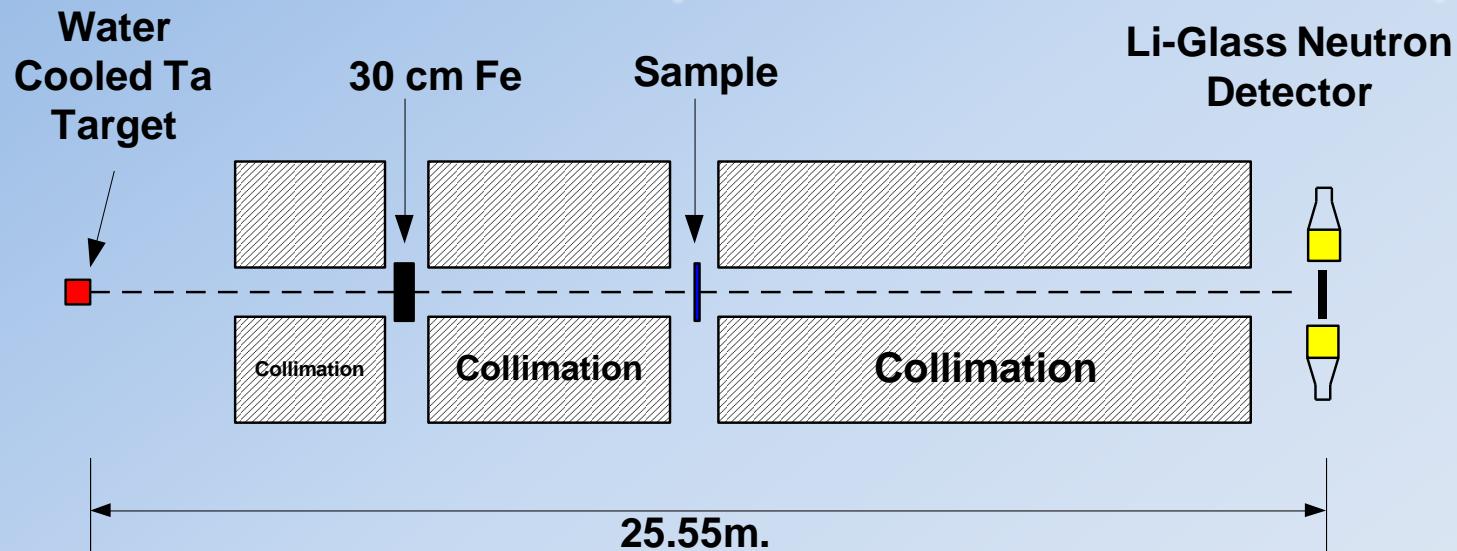
# Zr Total Cross Section Measurements (0.5-20 MeV)



- Used low Hf (less than 100 ppm) Zr metal
- ENDF/B 6.8 seems like a better fit for  $E < 16$  MeV
- New partially resolved structure below 2.0 MeV
- Data can be used to improve the unresolved resonance region evaluation



# Iron Filter Experimental Setup



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# Filtered Beam

- The total cross section exhibits strong minima because of resonance-potential interference.
- To Illustrate, use the single level Breit-Wigner formula:

$$\sigma_t(x) = \frac{\sigma_0}{x^2 + 1} \left[ 1 + 2x \frac{R}{\lambda} \right] + \sigma_{pot}$$

Where

$$x = \frac{2(E - E_0)}{\Gamma} \quad \sigma_0 = 4\pi\lambda_0^2 g \frac{\Gamma_n}{\Gamma}$$

$E_0$  - resonance peak energy

$R$  - effective nuclear radius

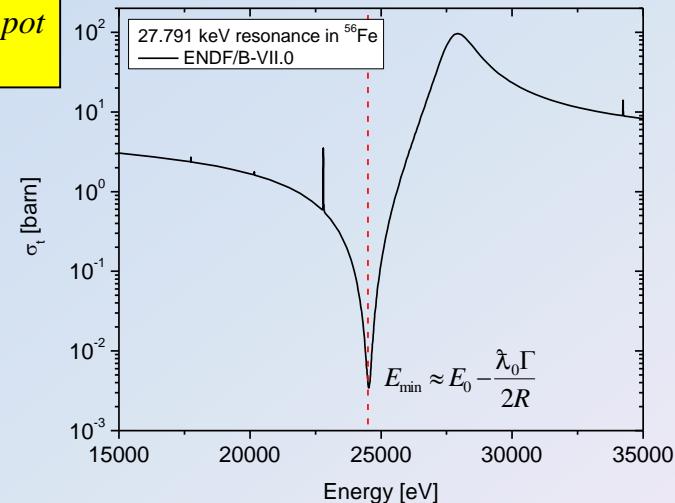
$\Gamma, \Gamma_n$  - total width and neutron width

$\lambda$  - reduced neutron width

$\lambda_0$  - reduced neutron width et energy  $E_0$

The energy at the minimum:

$$x_{min} \approx -\frac{\lambda_0}{R}$$



$$E_{min} \approx E_0 - \frac{\lambda_0 \Gamma}{2R}$$

The cross section at the minimum:

$$\sigma_{min} \approx \sigma_{pot} - \frac{\sigma_0}{(\lambda/R)^2 + 1}$$

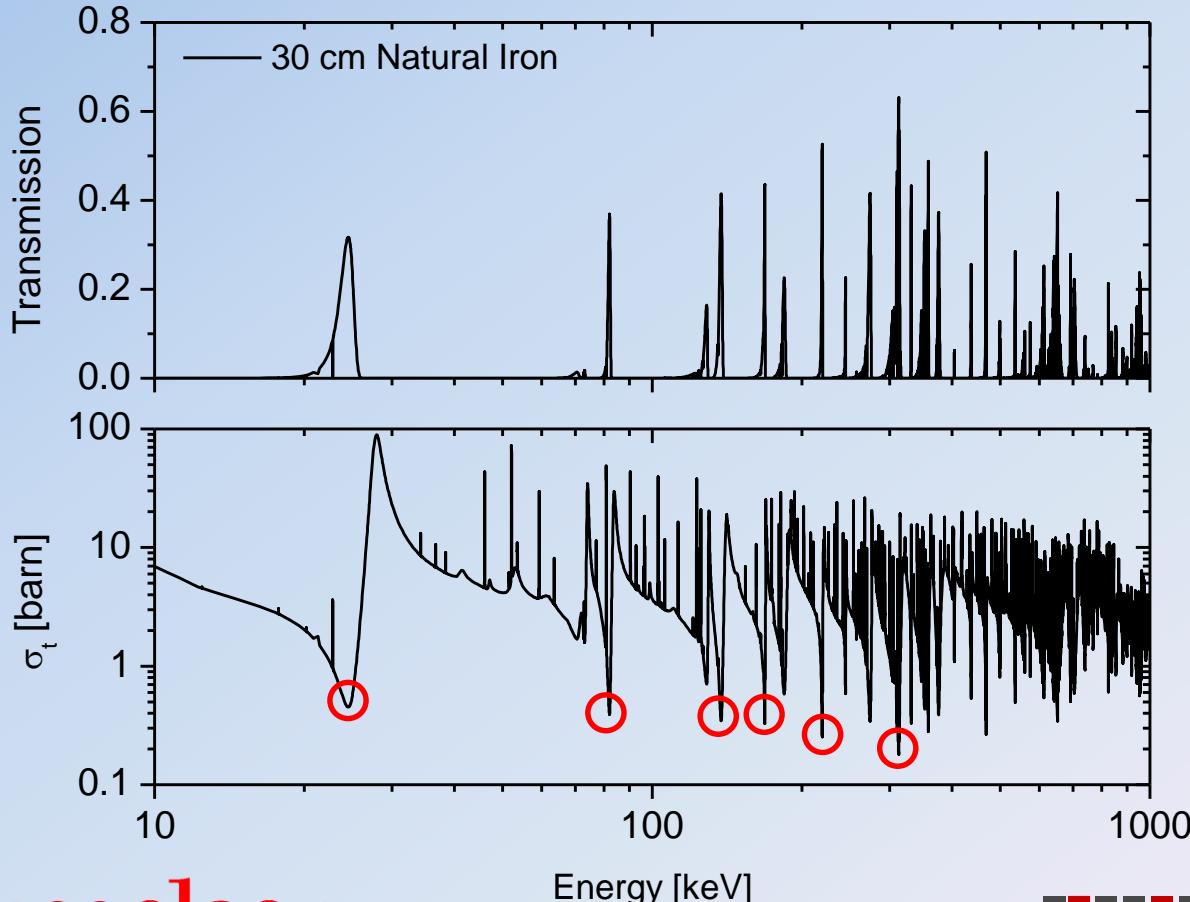


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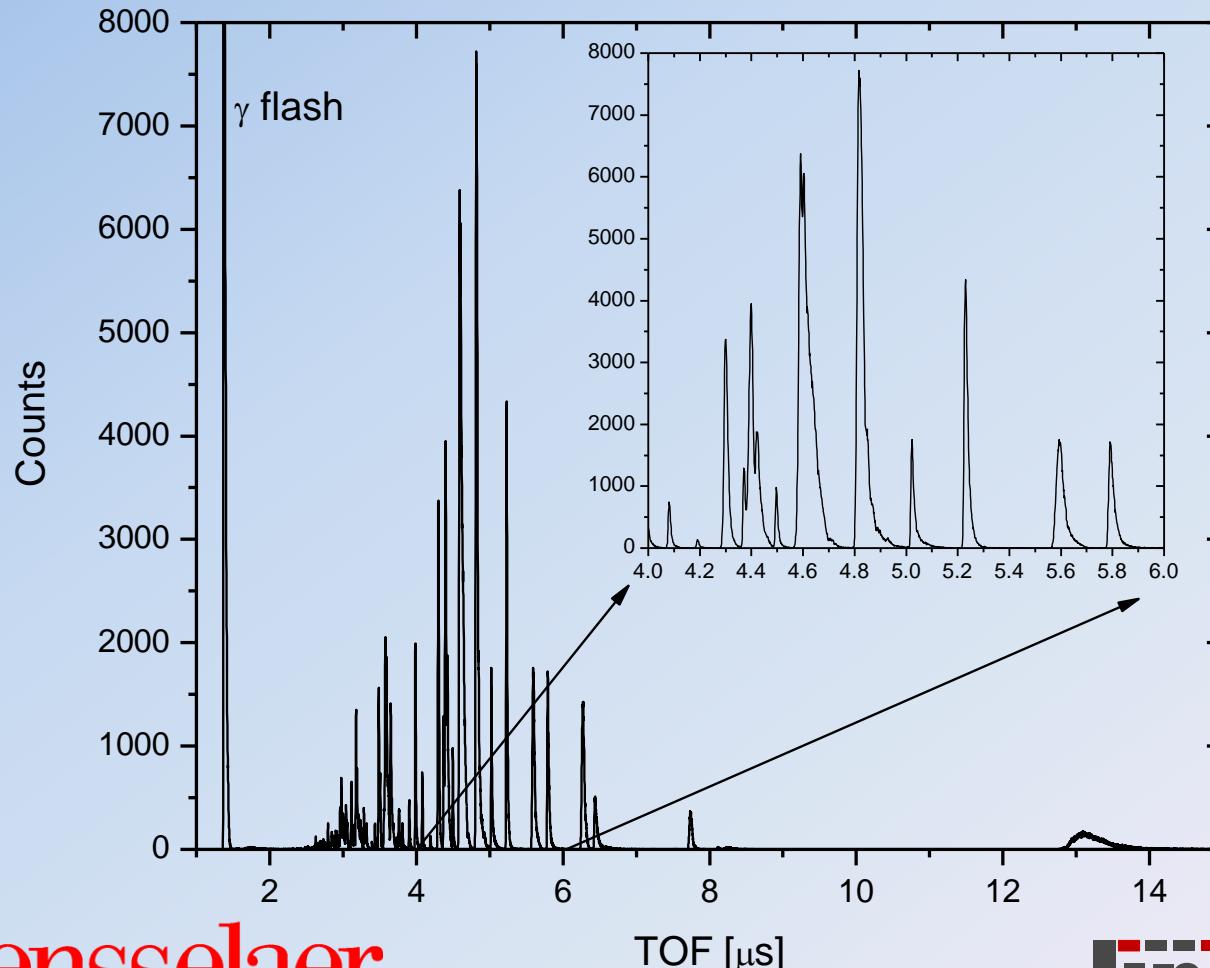
# Natural Iron Filter

- The total cross section exhibits strong minima because of resonance-potential interference

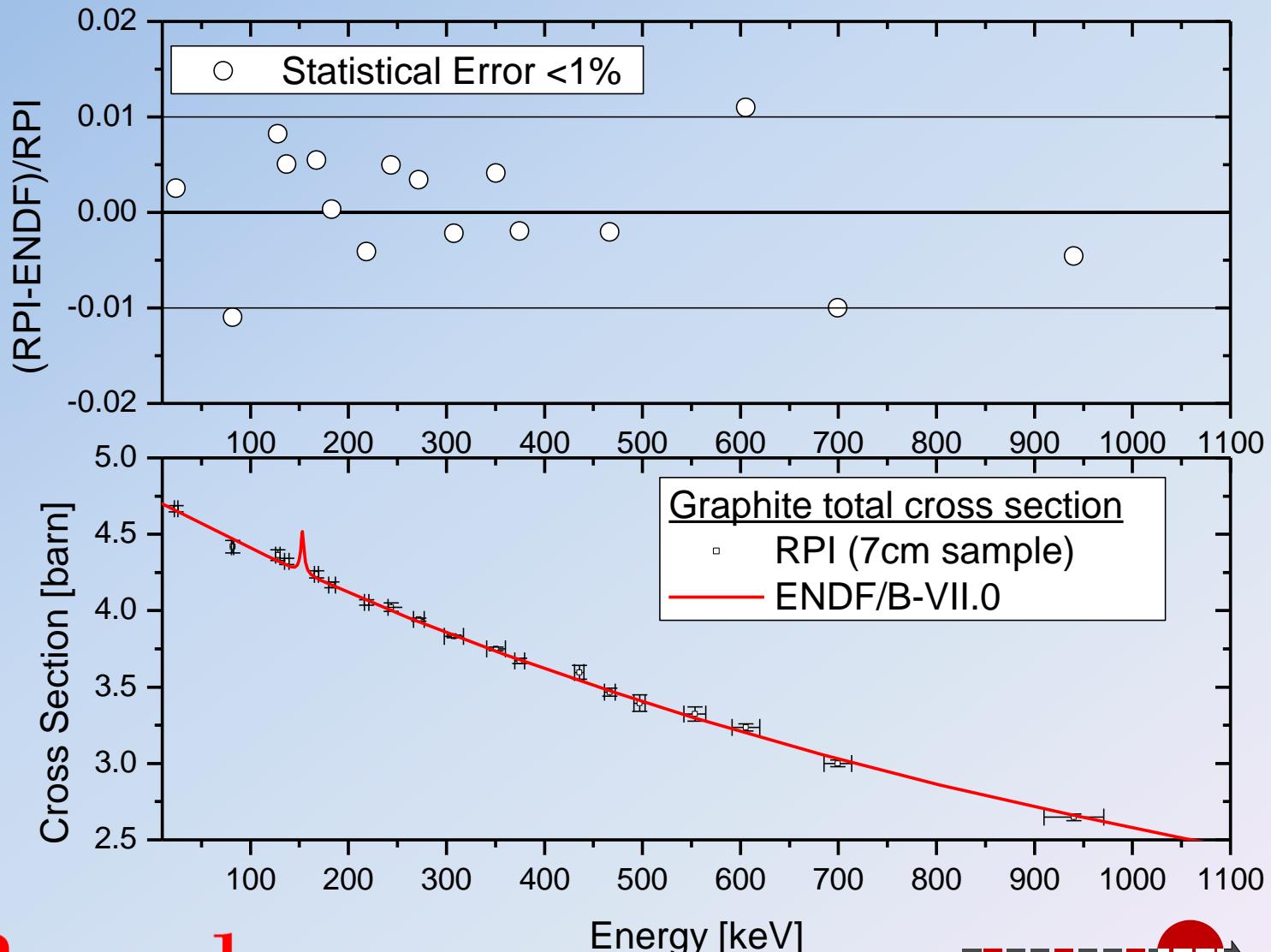


# Experimental Data

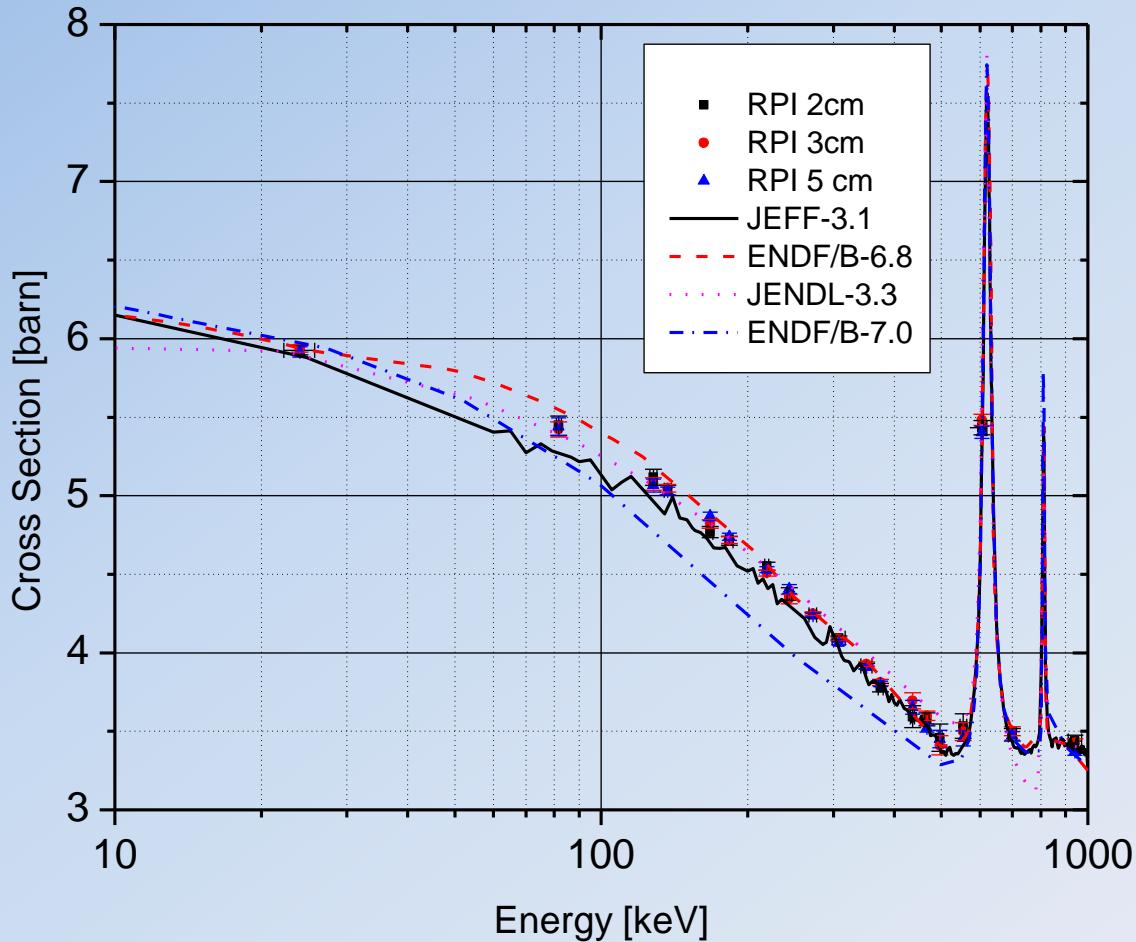
- Iron filtered beam data
  - Peaks are broadened by the TOF resolution function
  - High signal-to-background ratio



# Results - Graphite



# Results - Beryllium

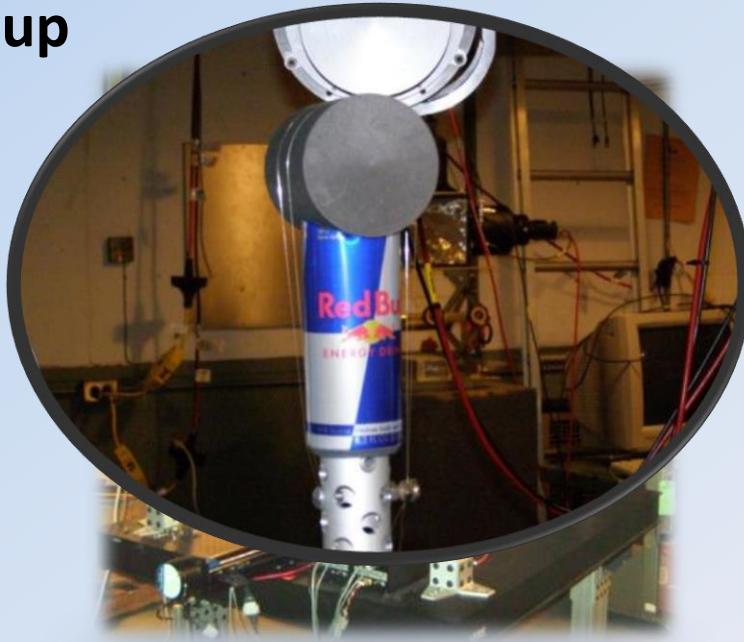


Y. Danon , R. C. Block, M. J. Rapp, and F. J. Saglime, G. Leinweber, D. P. Barry, N. J. Drindak and J. G. Hoole, “Beryllium and Graphite High Accuracy Total Cross-Section Measurements in the Energy Range from 24 keV to 900 keV”, Nuclear Science And Engineering, **161**, 321–330, (2009).



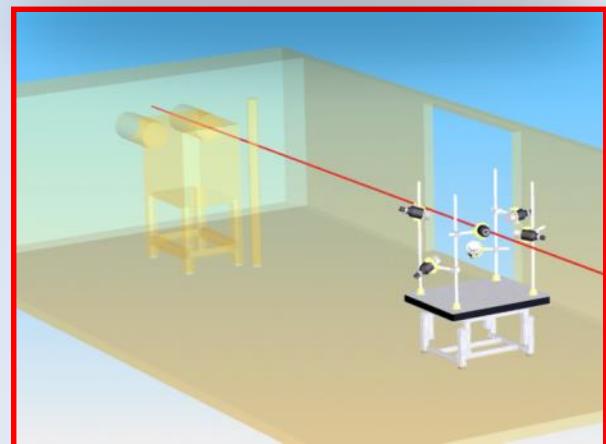
# Scattering Detection System: Experimental Setup

- **Detector Array**
  - 8 EJ301 Liquid Scintillation Detectors
  - 8 A/D channels
  - Pulse Shape discrimination in TOF
- **Measures neutrons scattered from the sample at different angles**
- **Measured scattered neutron energy 0.5 MeV - 20 MeV**
- **Results are compared with a Monte Carlo simulation of the system**



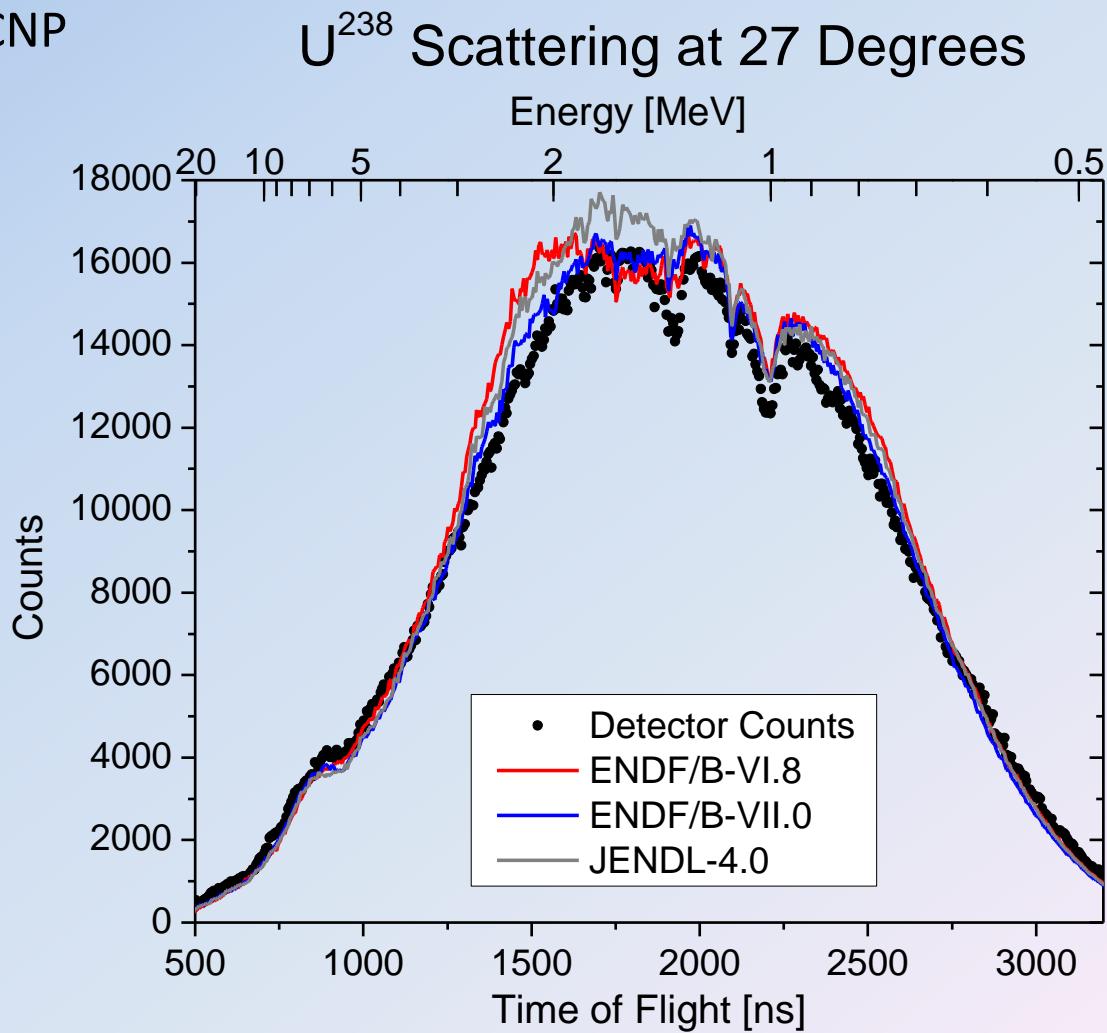
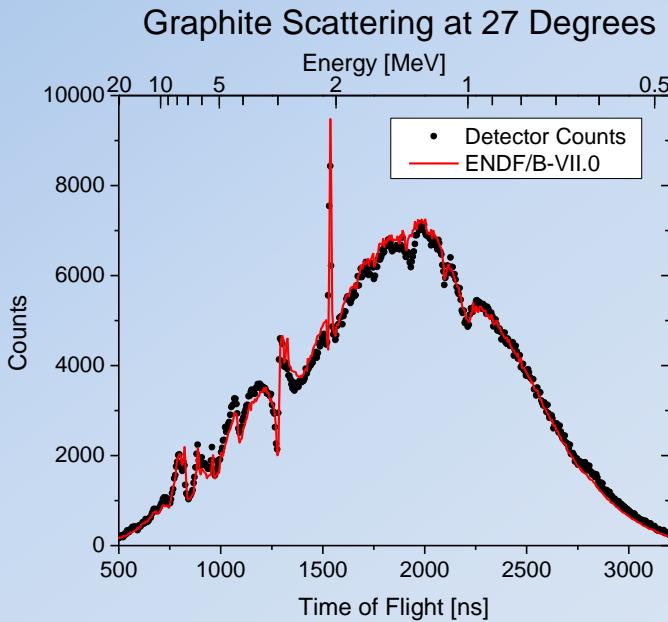
D. P. Barry, G. Leinweber, R. C. Block, and T. J. Donovan, Y. Danon, F. J. Saglime, A. M. Daskalakis, M. J. Rapp, and R. M. Bahran, "Quasi-differential Neutron Scattering in Zirconium from 0.5 MeV to 20 MeV", Nuclear Science and Engineering, 174, 188–201, (2013).

F.J. Saglimen, Y. Danon, R.C. Block, M.J. Rapp, R.M. Bahran, G. Leinweber, D.P. Barry and N.J. Drindak, "A system for differential neutron scattering experiments in the energy range from 0.5 to 20 MeV", Nuclear Instruments and Methods in Physics Research Section A, 620, Issues 2-3, Pages 401-409, (2010)



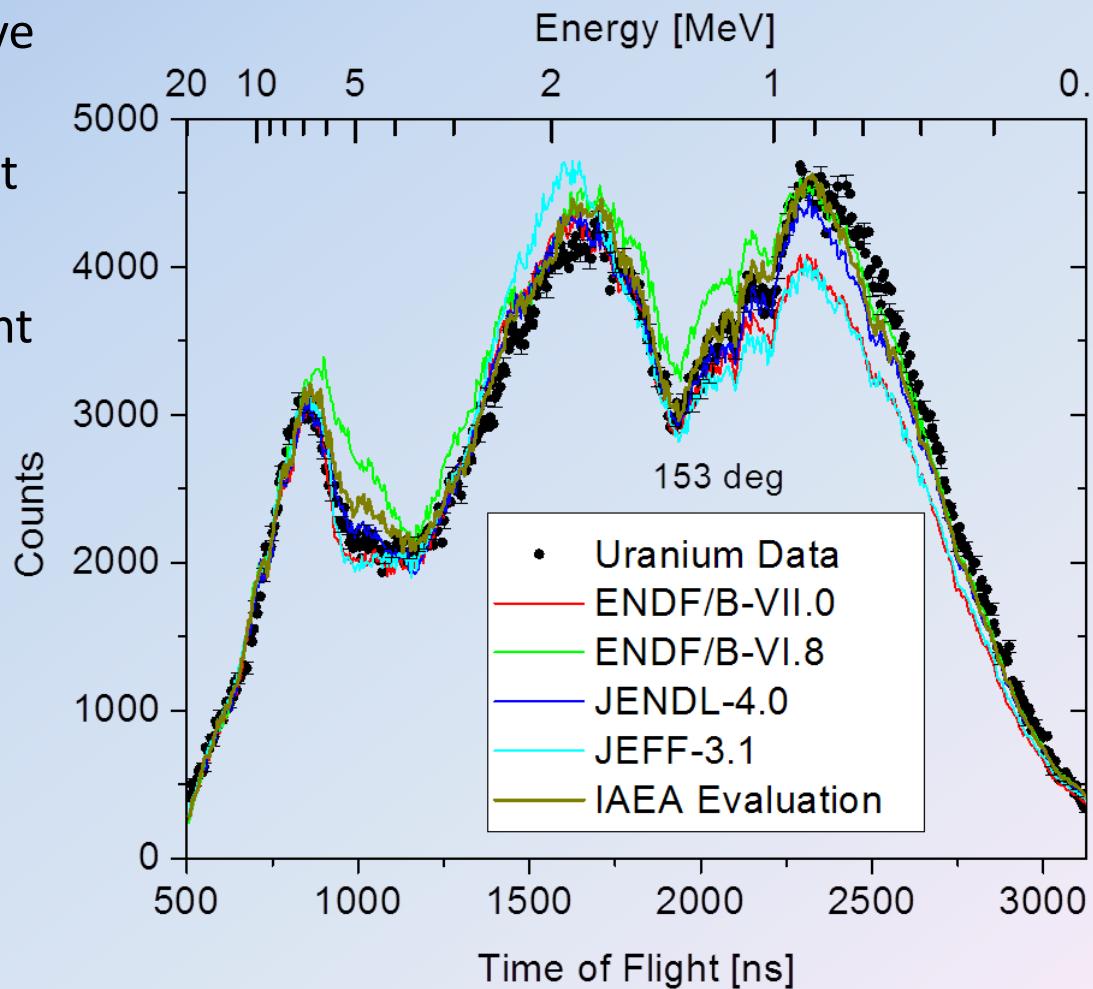
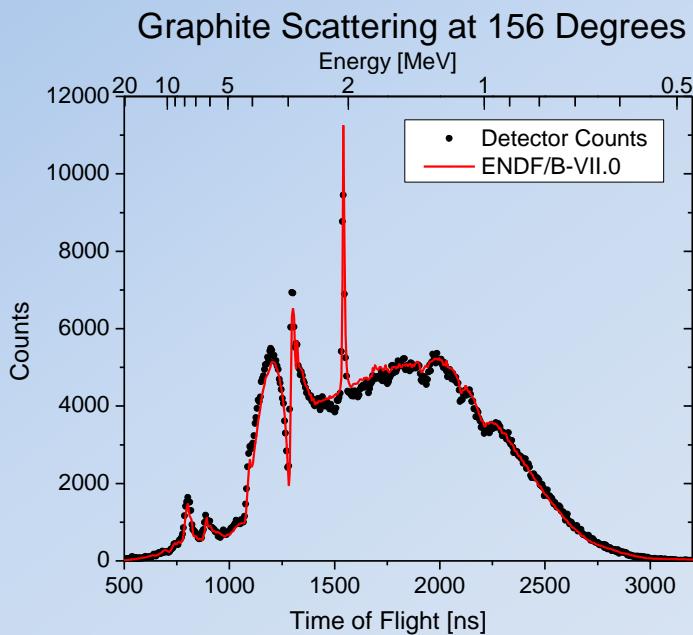
# $^{238}\text{U}$ Scattering at 27 Degrees

- Measured in September 2011.
- Compare measured data to MCNP simulations
- Use Carbon for verification of system and methodology
- ENDF/B-VII.0 has the best fit to the data



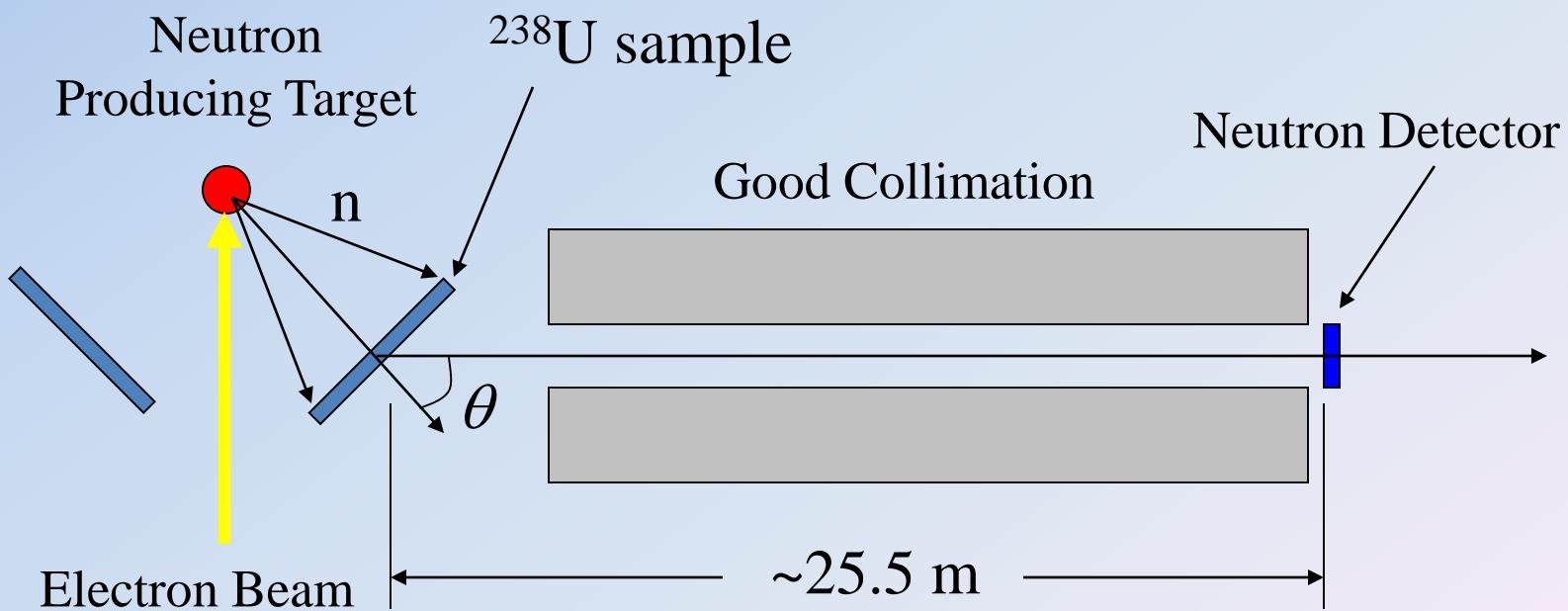
# $^{238}\text{U}$ Scattering at 156 Degrees

- New vacuum flight tubes improve the S/N
- ENDF/B-VI.8 provides the best fit
- JENDL-4.0 fits well for  $E < 3$  MeV
- ENDF/B-VII.0 needs improvement

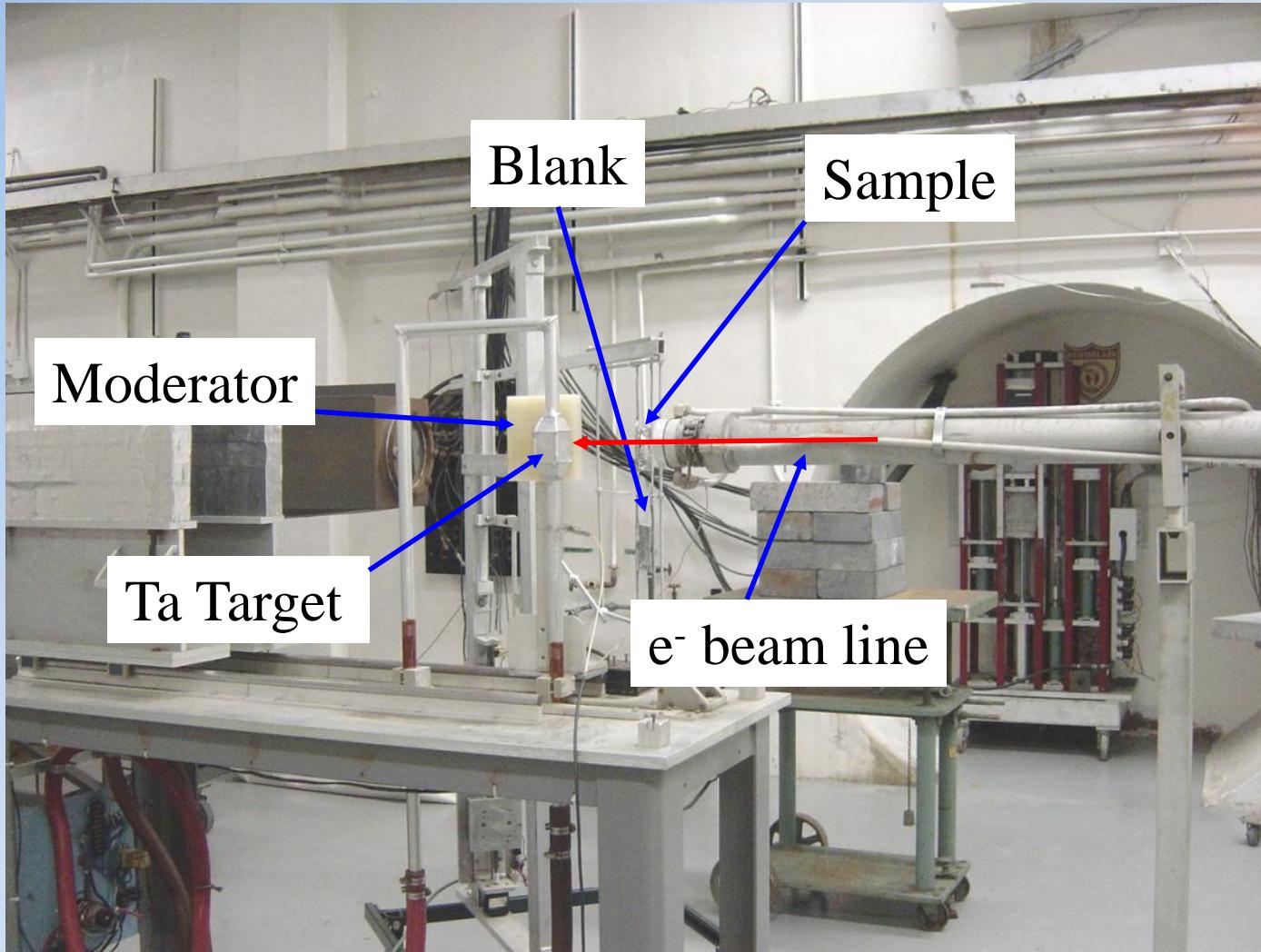


# Resonance Scattering Experiment

- Motivation – Provide a benchmark to the model Developed by **Dagan et al.**
  - Poor approximation of the scattering kernel when the cross section is energy dependent.
- Use the Time-Of-Flight (TOF) method
  - The TOF will correspond to the scattered neutron energy
  - Scattering in forward and backward scattering angles can be measured

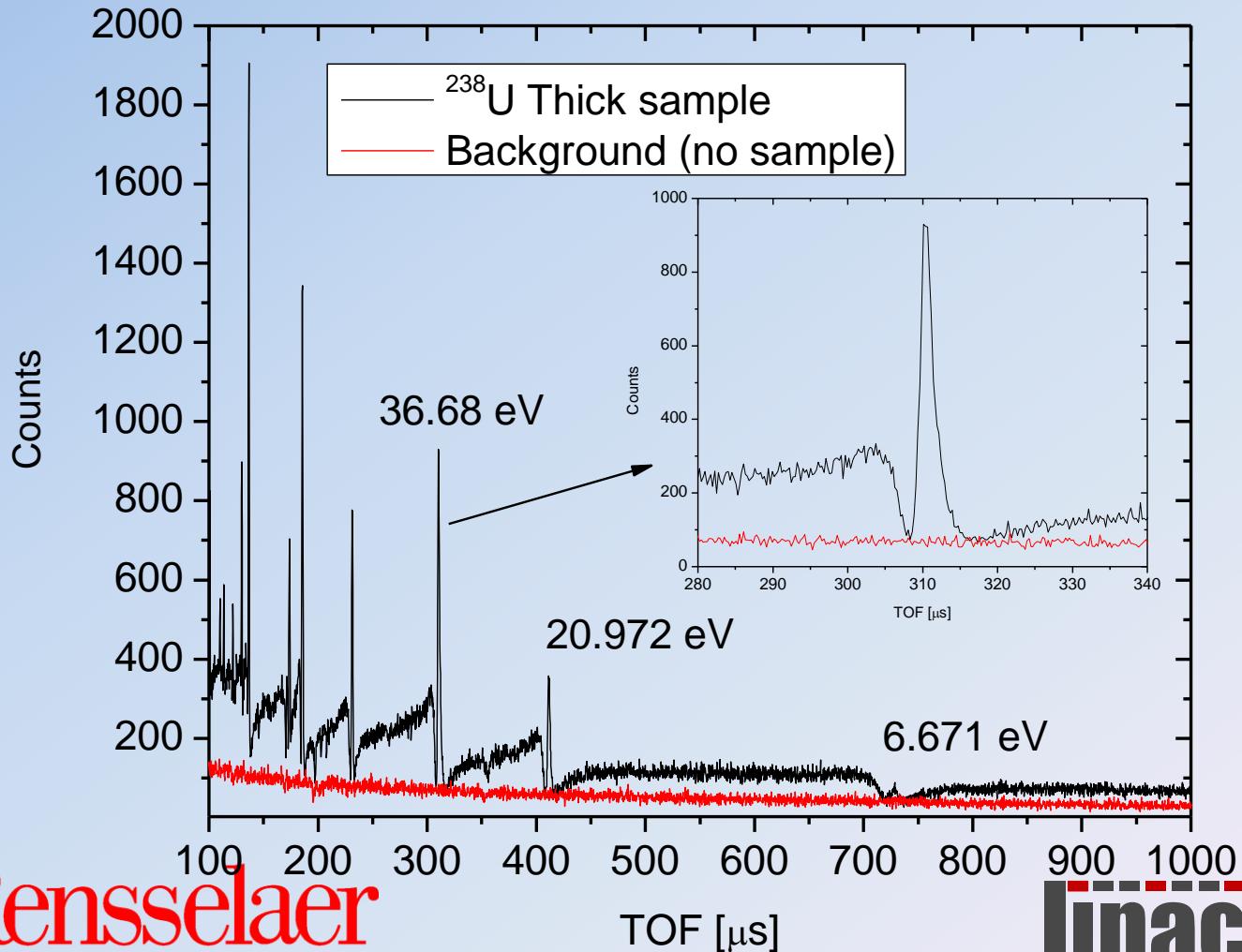


# Resonance Scattering- Experimental Setup

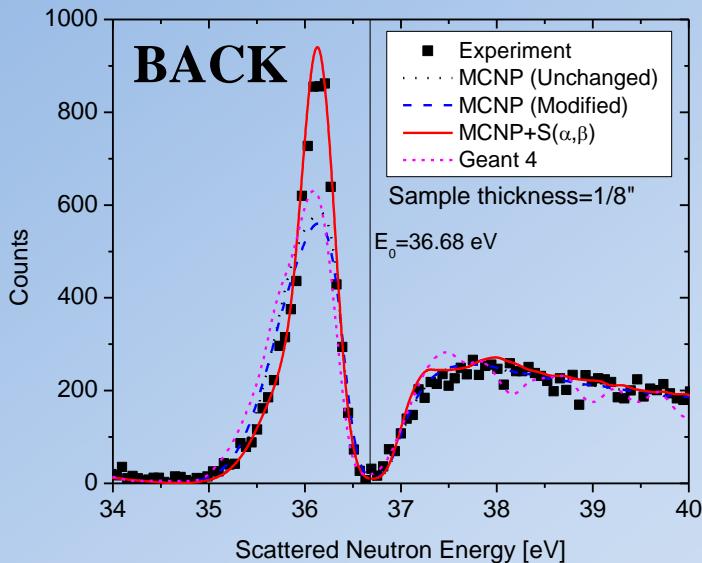


# Resonance Scattering-Measured Data

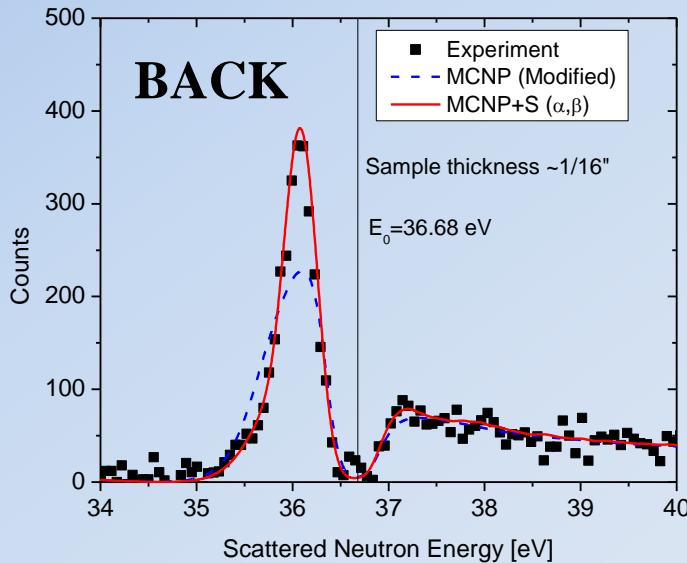
- Thick Sample time-of flight spectrum forwards scattering



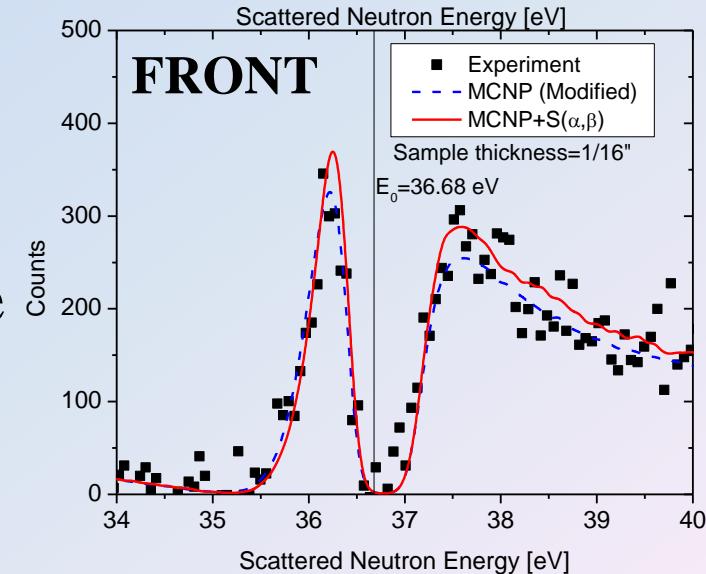
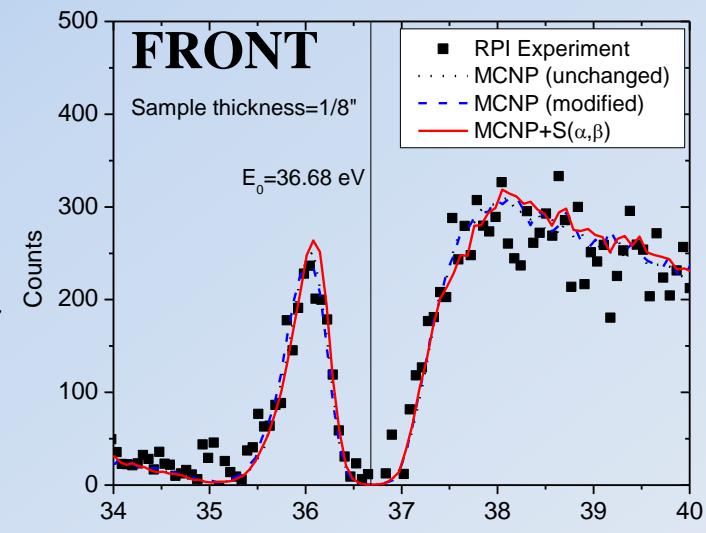
# Resonance Scattering - Results for $^{238}\text{U}$ Scattering



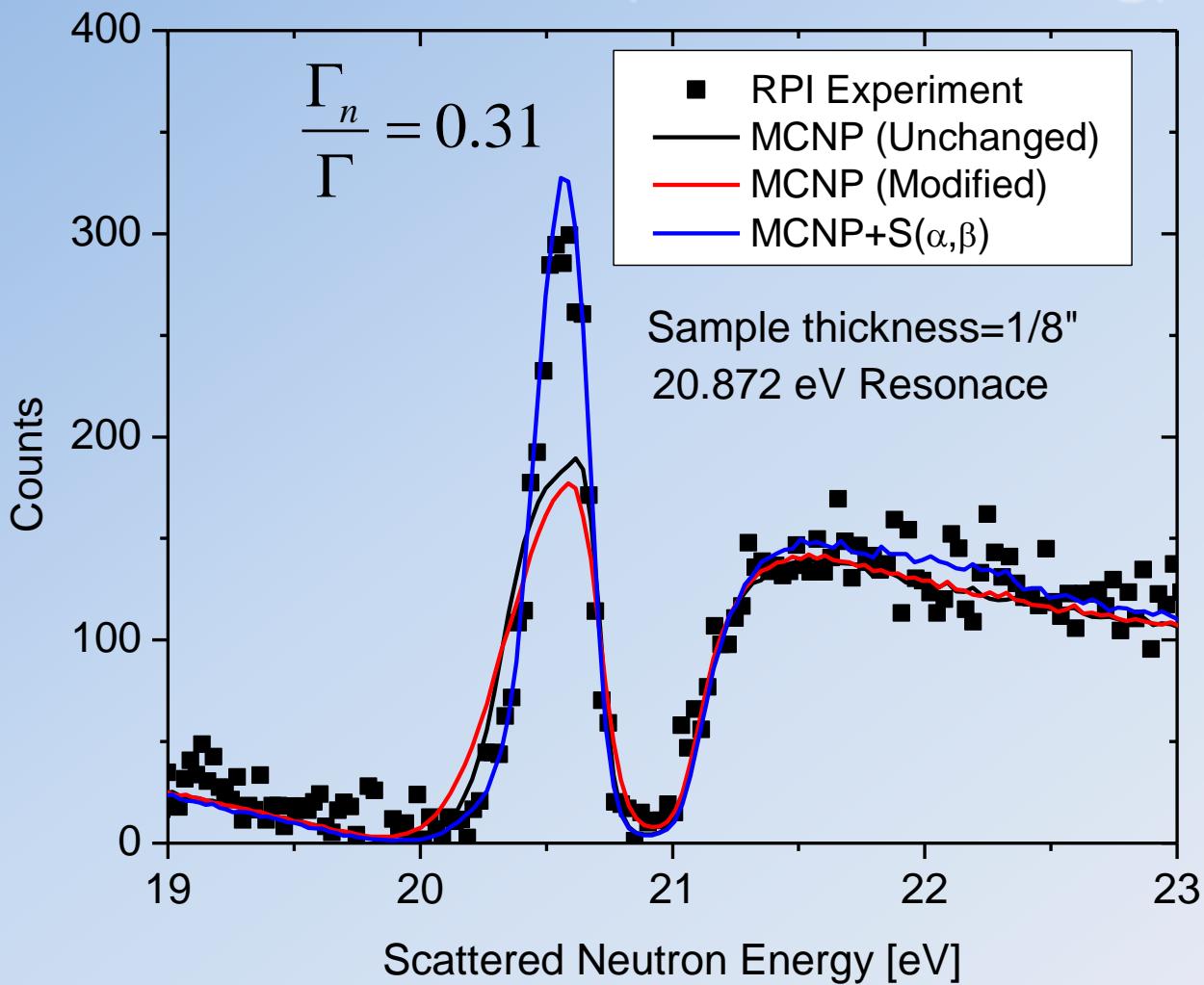
Thick  
Sample



Thin  
Sample

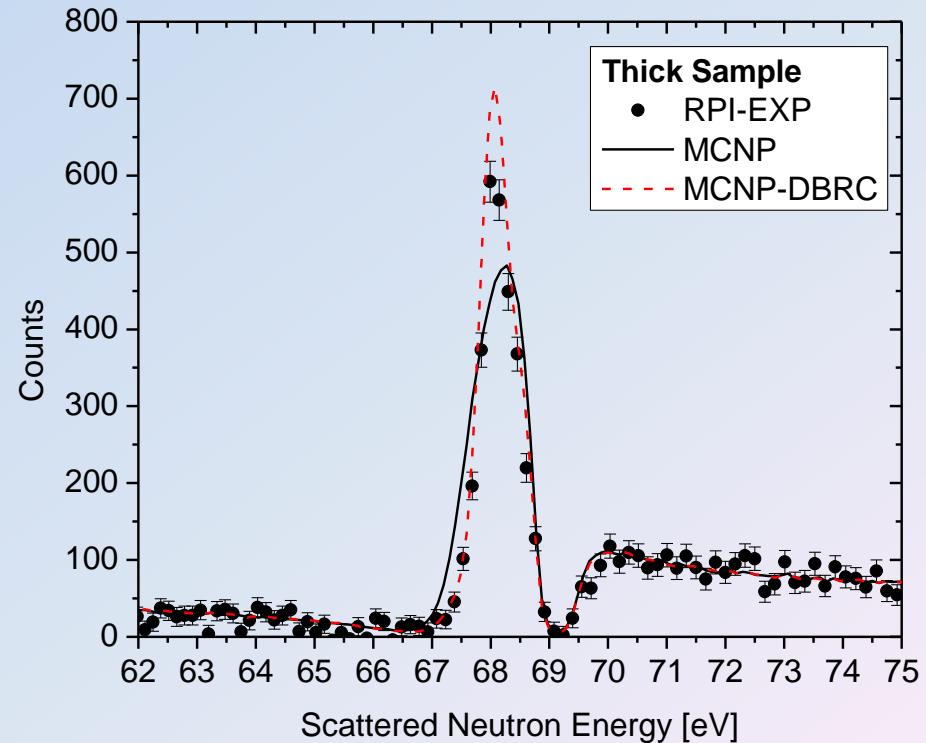
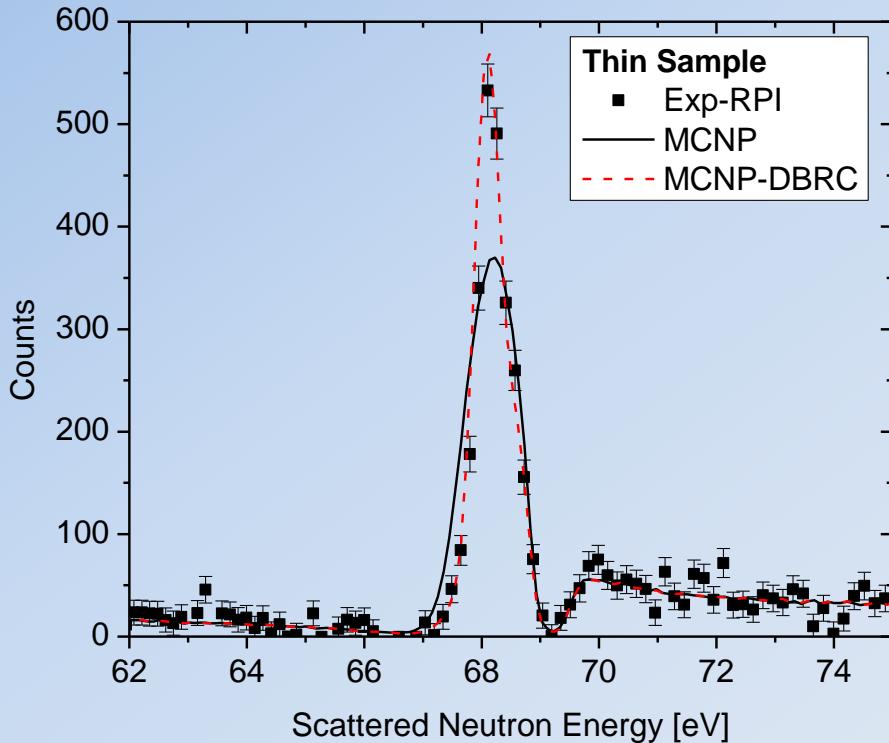


# Resonance Scattering - Other $^{238}\text{U}$ Resonances (Back Scattering)



# Thorium Backscattering Experimental Results

- Two sample thicknesses were used
- The backscattering angle was  $140.8^\circ$  and no moderator
- Experimental data was compared to current MCNP Doppler broadening and the new Doppler Broadening Rejection Correction (DBRC) method implemented by Dagan in MCNP 5
- The DBRC method is in good agreement with the experiments

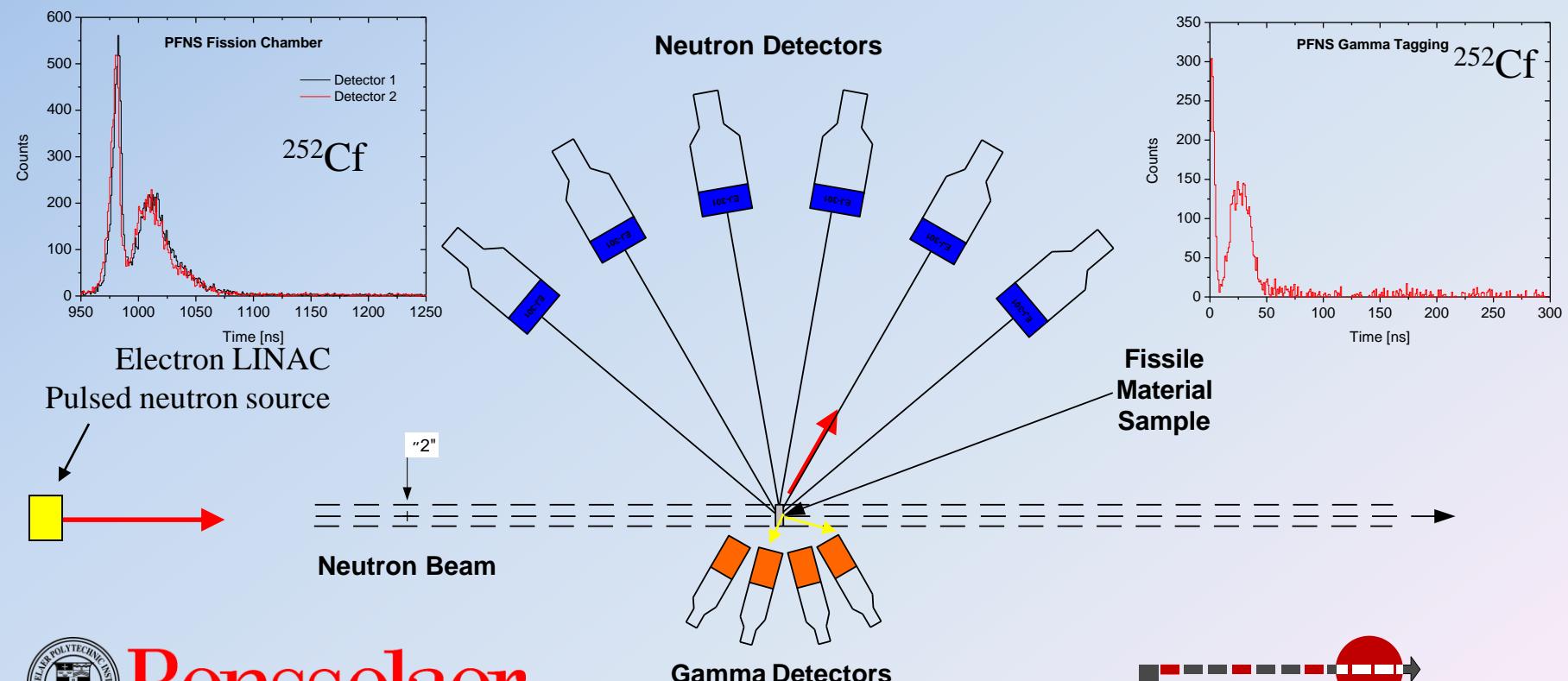


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# Fission Spectrum and Multiplicity Measurements

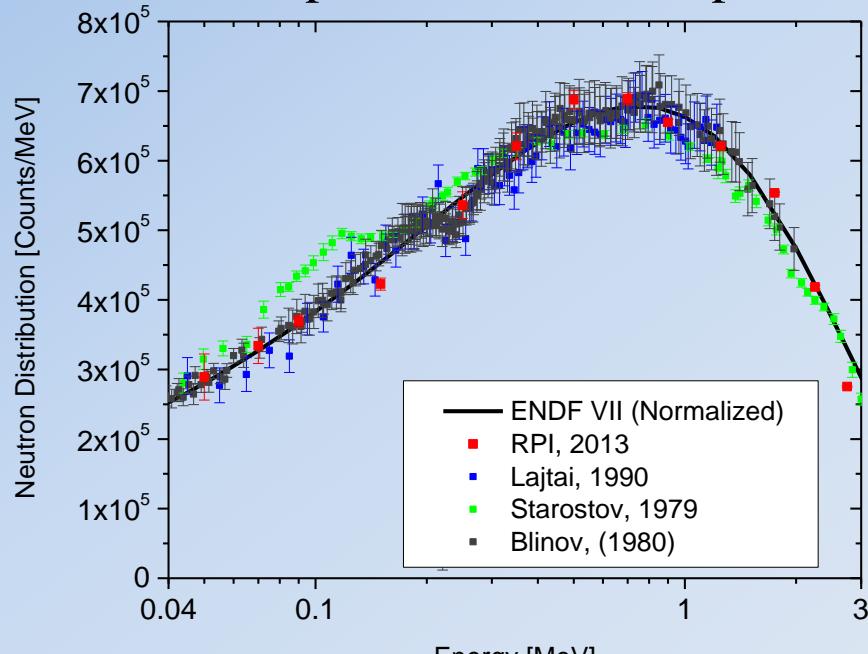
- Use the double TOF method
- Use a gamma tag for fission
- Use a combination of Liquid Scintillators and Li-Glass neutron detectors
- Same system will be used for inelastic scattering measurement



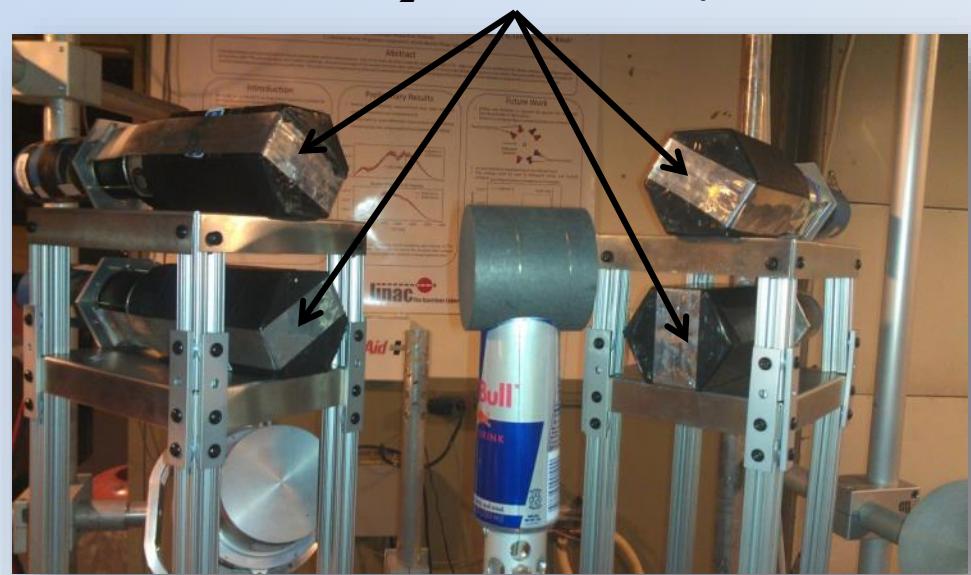
# Measurement of $^{252}\text{Cf}$ Prompt Fission Neutron Spectrum

- A preliminary step  $^{252}\text{Cf}$  was measured using the fission chamber as a fission tag.
- This kind of data will be compared with measurements using the gamma tag.
- EJ-301 measurements agree with ENDF/B-VII.1 from 5 MeV to 1 MeV while EJ-204 measurements extend the agreement down to 0.2 MeV

$^{252}\text{Cf}$  Prompt fission neutron spectrum

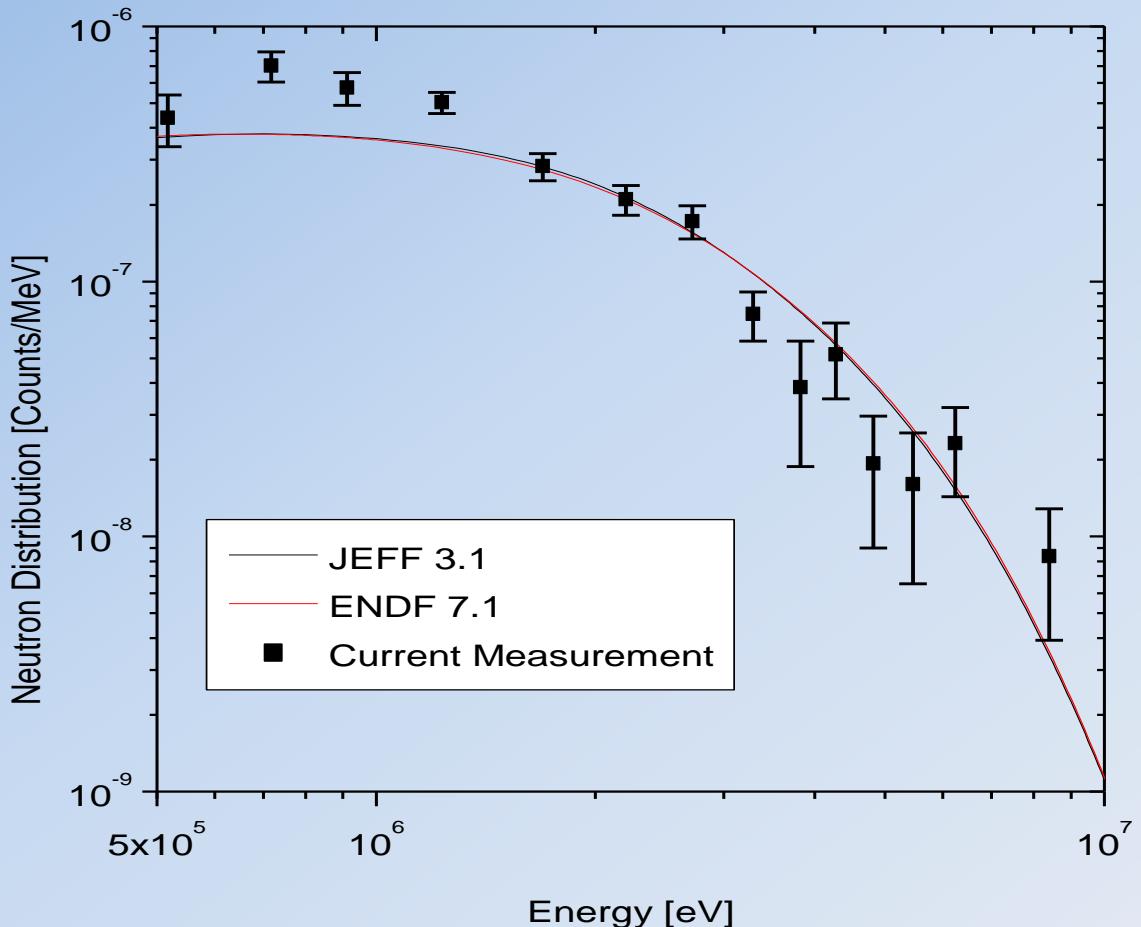


$\text{BaF}_2$  detector array



# $^{238}\text{U}$ Prompt Fission Neutron Spectrum High Energy

## Preliminary Results



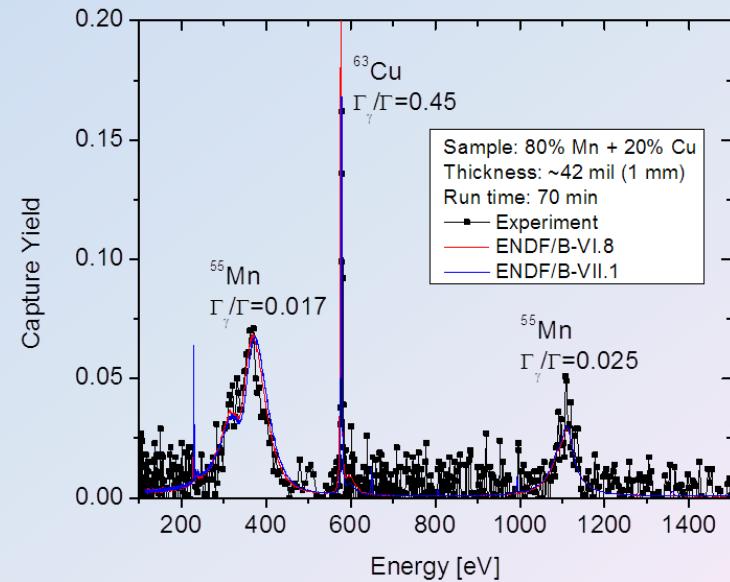
- Spectrum is normalized to ENDF at 2 MeV
- Spectrum is integrated over all incident time-of-flights ( $\sim E^n > 1.5$  MeV)
- Preliminary data shows good agreement with current evaluations
- Pulse shape discrimination used to discriminate against gamma pulses
- Error bars shown include only statistical uncertainty



# New 45m keV Energy Range Capture Detector



- 4 deuterated benzene ( $C_6D_6$ ) liquid scintillators with low neutron sensitivity
- Located at newly constructed 40m flight station
- 10-bit, 8 channel Struck Systems SIS3305 digital data acquisition system allows for low dead time operation
- Low mass design to minimize background contributions from neutrons captured in detector and surrounding structural materials



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# Thank you



# Nuclear Data related Publications (partial list)

- Fission
  - C. Romano, Y. Danon, R. Block, J. Thompson, E. Blain, E. Bond, "Fission Fragment Mass And Energy Distributions As A Function of Neutron Energy Measured In A Lead Slowing Down Spectrometer", Phys. Rev. C 81, 014607 (2010).
  - B. Becker, P. Talou, T. Kawano, Y. Danon, I. Stetcu, "Monte Carlo Hauser-Feshbach Predictions of Prompt Fission Gamma Rays - Application to  $n\text{th}+235\text{U}$ ,  $n\text{th}+239\text{Pu}$  and  $252\text{Cf}$  (sf)", Phys. Rev. C, 87, 1, 014617 August (2013).
- LSDS
  - J.T. Thompson, T. Kelley, E. Blain, R.C. Haight, J.M. O'Donnell, Y. Danon, "Measurement of  $(n,\alpha)$  reactions on  $^{147}\text{Sm}$  and  $^{149}\text{Sm}$  using a lead slowing-down spectrometer", Nuclear Instruments and Methods in Physics Research Section A, Volume 673, Pages 16-21, 1 May (2012)
- Neutron Scattering
  - D. P. Barry, G. Leinweber, R. C. Block, and T. J. Donovan, Y. Danon, F. J. Saglime, A. M. Daskalakis, M. J. Rapp, and R. M. Bahran, "Quasi-differential Neutron Scattering in Zirconium from 0.5 MeV to 20 MeV", Nuclear Science and Engineering, 174, 188–201, (2013).
  - F.J. Saglime, Y. Danon, R.C. Block, M.J. Rapp, R.M. Bahran, G. Leinweber, D.P. Barry and N.J. Drindak, "A system for differential neutron scattering experiments in the energy range from 0.5 to 20 MeV", Nuclear Instruments and Methods in Physics Research Section A, 620, Issues 2-3, Pages 401-409, (2010).
- Eu
  - G. Leinweber, D.P. Barry, J.A. Burke, M.J. Rapp, R.C. Block, Y. Danon, J.A. Geuther, F.J. Saglime III, "Europium resonance parameters from neutron capture and transmission measurements in the energy range 0.01–200 eV", Annals of Nuclear Energy, Volume 69, July 2014, Pages 74-89, ISSN 0306-4549
- Mo
  - G Leinweber, DP Barry, JA Burke, NJ Drindak, RC Block, Y Danon, BE Moretti, "Resonance Parameters and Their Uncertainties Derived from Epithermal Neutron Capture and Transmission Measurements of Elemental Molybdenum", Nuc. Sci. Eng., 164, 287-303, (2010).
  - G. Leinweber, D.P. Barry, J.A. Burke(ret.), N.J. Drindak, R.C. Block, Y. Danon, B.E. Moretti, "Measurements of elemental molybdenum and resonance parameter analysis", International Conference on Nuclear Data for Science and Technology (ND2007), April 22-27, Nice, France, (2007)
- C & Be
  - M.J. Rapp, Y. Danon, F.J. Saglime, R.M. Bahran and D.G. Williams, G. Leinweber, D.P. Barry and R.C. Block, "Beryllium and Graphite Neutron Total Cross Section Measurements from 0.4 to 20 MeV", Nuclear Science and Engineering, Vol. 172, No. 3. Pages 268-277, November 2012 (2012).
  - Y. Danon , R. C. Block, M. J. Rapp, and F. J. Saglime, G. Leinweber, D. P. Barry, N. J. Drindak and J. G. Hoole, "Beryllium and Graphite High Accuracy Total Cross-Section Measurements in the Energy Range from 24 keV to 900 keV", Nuclear Science And Engineering, 161, 321–330, (2009)
  - Y. Danon, R.C. Block, M. Rapp, F. Saglime, D.P. Barry, N.J. Drindak, J. Hool, G. Leinweber, "High-Accuracy Filtered Neutron Beam and High-Energy Transmission Measurements at the Gaerttner Laboratory", submitted to the International Conference on Nuclear Data for Science and Technology, April 22-27 2007, Nice, France
- Gd using diluted samples enriched with 155 and 157.
  - G. Leinweber, D.P. Barry, M.J. Trobovich, J.A. Burke, N.J. Drindak, , HD Knox, RV Ballad, R.C. Block, Y. Danon, L.I. Severnyak, "Neutron Capture and Total Cross-Section Measurements and Resonance Parameters of Gadolinium" ., Nuc. Sci Eng. 154, 261-279 (2006).
- Nb
  - N.J. Drindak, J.A. Burke, G. Leinweber, J.A. Helm, J.G. Hoole, R.C. Block, Y. Danon, R.E. Slovacek, B.E. Moretti, C.J. Werner, M.E. Overberg, S.A. Kolda, M.J. Trobovich, D.P. Barry, "Neutron Capture and Transmission Measurements and Resonance Parameter Analysis of Niobium", Nuc. Sci Eng. 154, 294-301 (2006).
- Nd
  - D. P. Barry, M. J. Trbovich, Y. Danon, R. C. Block, R. E. Slovacek, G. Leinweber, J. A. Burke, N. J. Drindak, "Neutron Capture and Total Cross-Section Measurements and Resonance Parameter Analysis of Neodymium from 1.0 eV TO 500 eV", The Tenth International Conference on Radiation Shielding and Radiation Protection & Shielding Topical (ICRS10 / RPS-2004), Madeira, Portugal, May 9-14, (2004)
  - D. P. Barry, M. J. Trbovich, Y. Danon, R. C. Block, R. E. Slovacek, G. Leinweber, J. A. Burke, N. J. Drindak, "Neutron Transmission and Capture Measurements and Resonance Parameter Analysis of Neodymium From 1.0 eV To 500 eV". Nuclear Science And Engineering: 153, 8-2, (2006)
- Hf
  - M. J. Trbovich, D. P. Barry, R.E. Slovacek, Y. Danon, R. C. Block, N. C. Francis, M Lubert, J. A. Burke, N. J. Drindak, G. Leinweber, R. Ballad, "Hafnium Resonance Parameter Analysis Using Neutron Capture and Transmission Experiments" Nuclear Science And Engineering, 161, 303–320, (2009).
- Sm
  - S. Wang, M. Lubert, Y. Danon, N. C. Francis, R. C. Block, F. Becvar, M. Krticka, "The RPI multiplicity detector response to  $\gamma$ -ray cascades following neutron capture in  $^{149}\text{Sm}$  and  $^{150}\text{Sm}$ ", NIM A 513/3 pp. 585-595, (2003)
  - Leinweber, G., Burke, J.A., Knox, H.D., Drindak, N.J., Mesh, D.W., Haines, W.T., Ballard, R.V., Block, R.C., Slovacek, R.E., Werner, C.J., Trbovich, M.J. Barry, D.P. and Sato, T., "Neutron Capture and Transmission Measurements and Resonance Parameter Analysis of Samarium," Nuclear Science and Engineering, 142, 1-21, 2002

